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A practical approach to the efficient use of heavy fuel oils in diesel engine plants

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A PRACTICAL APPROACH TO THE EFFICIENT USE OF HEAVY FUEL OILS IN DIESEL ENGINE PLANTS

BY

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I certify that all material in this dissertation which is not my own work has been identified and that no material is included for which a degree has been previously conferred upon me.

The contents of this dissertation reflect my personal views and are not necessarily endorsed by the University.

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DEDICATION

This dissertation is dedicated to my dear parents the Rev. J. Gargar and E. Mardea Thomson Barchue. Their struggle for survival amidst the horrifying Liberian civil war, and my inability to locate and assist them gave me renewed impetus to succeed.

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ABSTRACT

The use of poor quality heavy fuel oil (HFO) in diesel engines has increased considerably over the last decade. This increase has been driven purely from the immediate financial benefits associated with the price of poor quality heavy fuels. The notion of 'if it burns, use it' has led to catastrophic and irreversible damages to many engine components.

Compounding the former dilemma is the inadequate knowledge of some operators with respect to the qualities of HFOs and their effects on diesel engines. Secondly, some educational institutions responsible for educating these operators have not developed the appropriate courses to address this issue.

It is than evident that there is a need to develop a practical and comprehensive discourse on this subject. The essence of this discourse will be to provide the would be operator and the practising operator with the knowledge necessary to efficiently manage the use of HFOs in diesel engine plants.

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LIST OF ACRONYMS

ASTM	American Society for Testing and Materials
BHPH	Brake Horse Power Hour
BIMCO	Baltic International Maritime Charterer's Organization
BMEP	Brake Mean Effective Power
BSI	British Standards Institution
CA	Crank Angle
CBS	Conventional Booster System
CCAI	Calculated Carbon Aromaticity Index
CIMAC	International Council on Combustion Engines
cSt	Centistokes
DNV	Det Norske Veritas
FOBAS	Fuel Oil Bunker Analysis Services
FCC	Fluidized Catalytic Cracking
HFOs	Heavy Fuel Oils
HFO-SYS	Heavy Fuel Oil System
ICS	International Chamber of Shipping
IFO	Intermediate Fuel Oil
IP	Institute of Petroleum
ISO	International Standard Organization
MCR	Maximum Continuous Rating
MDO	Marine Diesel Oil
MSE	Medium Speed Four Stroke Diesel Engine
MTBO	Mean Time Between Overhaul
NO_x	Nitrogen Oxides
OH	Hydroxl Radicals
PBS	Pressurized Booster System
PODC	Planning, Organizing, Directing and Controlling
PPM	Parts Per Million
RPM	Revolutions Per Minute
SAE	Society of Automotive Engineers

SCR	Selective Catalytic Reduction
SFOC	Specific Fuel Oil Consumption
SHFT	Shell Hot Filtration Test
SO_x	Sulphur Oxides
SSD	Slow Speed Two Stroke Diesel Engine
TBN	Total Base Number
VFQTP	Veritas Fuel Quality Testing Programme
VIT	Variable Injection Timing

CHAPTER I

INTRODUCTION

For well over half a century the diesel engine has served as a dependable fossil fuel based heat engine. The performance of this engine until recently has been based on the reliability and durability of its components. Its deployment as the preferred marine propulsion machinery stemmed from the fact that the thermal energy conversion process occurred in one piece of machinery. Secondly, the theoretical thermal efficiency of this dual-cycle heat engine was noticeably higher compared to the then widely used Rankine cycle heat engine.

The economics of the initial investment cost of the diesel engine plant compared with the steam turbine plant (Rankine cycle) favored the diesel engine plant. An evaluation of the long term operational cost of these two engines revealed that the maintenance cost of the diesel engine plant virtually eliminated this positive edge. Further analysis confirmed that the higher thermal efficiency of the diesel engine only served to defray the cost of the relatively expensive and better quality fuel used compared with the cheaper and poorer quality fuel used in the steam turbine plant.

However, much of these considerations have changed in the past two decades. The thermal efficiency of the Rankine cycle heat engine could be as high or higher than the

dual-cycle heat engine. This theory could be realized if materials could allow for a sustained higher temperature comparable to the cyclic upper temperature of the dual-cycle engines.

With the developments in diesel engine technology, the reliability of engine components has improved with a corresponding decrease in the overall maintenance cost. Diesel engines are now capable of operating on extremely low quality fuels. Their thermal efficiency has been significantly increased with a subsequent increase in complexity and components of the diesel engine plant.

These developments are all good and well from the economic perspective. The extent to which these positive features can be sustained is invariably dependent upon the quality of the fuel used. For most of the operators of diesel engine plants, fuel qualities remain incongruous as to the origin of the respective quality parameters, their composition, their effect on engine performance and components as well as the applicable measures to systematicaly manage these varying qualities of fuels.

This incongruity is predicated on the lack of unanimity and completeness of the information which is disseminated to operators. In addition, most of the educational institutions responsible for molding the minds of the would be operators have not developed specific courses to address this issue.

Therefore, this dissertation will explore this issue by the use of an empirical method to develop a comprehensive working knowledge about heavy fuel oils (HFOs) and how to

expeditiously manage their use in diesel engine plants. This dissertation is divided into eight chapters and all illustrations associated with each chapter are placed in an appendix immediately following the chapter concerned.

Chapter II will discuss the origin and the process of producing HFOs. The naturally occurring undesirable components of HFOs and those components induced by the production process will be examined. The efforts of several professional organizations to establish independent specification parameters for HFO and their combined effort which culminated in the issuance of acceptable limits for the different qualities and grades of HFOs will be mentioned. The significance for establishing these quality parameters vis-a-vis the diesel engine plant will be introduced.

Chapter III will address the storage, transfer and treatment of HFOs. The difficulties encountered by operators as they attempt to manage these systems will be discussed. The applicable qualities of HFOs and their potential to affect the smooth operation of these systems will be examined. The design considerations for various components and the optimum configuration of these systems as well as the technological developments relative to specific components will be highlighted.

Chapter IV will continue the evaluation of the effects of HFO's qualities versus the design and operational considerations to minimize these effects in the booster and injection systems. The role of these two systems in conditioning the HFO for the combustion chamber process will be examined.

These two systems have undergone radical developments which have increased their operational complexity and their sensitivity to the contaminants of HFO. At the same time they condition the HFO and adjust to accommodate certain qualities of HFO. These interwoven intricacies of these systems vis-a-vis the management of this process will be discussed.

Chapter V will be dedicated to the review of the developments in slow speed two stroke diesel engine (SSE) combustion chambers and their ability to burn poor quality HFOs. Similar aspects with respect to exhaust gas user equipment are also considered.

An in depth discussion of the various components and qualities of HFOs as they affect the combustion process will be included in this chapter. The conditions under which detrimental by-products are formed and their effect on engine components vis-a-vis the relevant adjustable operational parameters and the inherent design features to minimize them will be discussed.

Chapter VI will be divided into two parts. Part I will unravel the specific design and operational aspects of medium speed four stroke diesel engines (MSE) abilities to burn HFO. These considerations will only be discussed where they differ from the SSE.

Part II of this chapter will be devoted to condition monitoring of diesel engines as a necessary element in promoting the efficient use of HFOs. The effects of diesel engines exhaust emissions on the environment and measures to reduce these effects will be mentioned.

Chapter VII will introduce basic management concepts to provide a working knowledge for the operator in dealing with the use of HFOs. The entire process from the purchasing of bunkers through and including exhaust emissions with respect to HFOs will be considered as a dynamic process which should be managed. The process to be managed will be called "The HFO-System" (HFO-SYS).

The HFO-SYS is subdivided into management models which are called planning, organizing, directing and controlling (PODC) models. The various systems, components and inter-related activities are grouped under the appropriate model. The management concepts, planned activities and fuel quality parameters relevant to each model are indicated accordingly. These process management models bring together all of the discussions from previous chapters to provide a solid format for the efficient use of HFO in diesel engine plants.

Chapter VIII will be a general conclusion which will underscore the need for institutions to include a comprehensive study of HFO in their curriculum. Emphasis will be placed on the testing of HFO and the translation of test results into proper actions by the operator. The need for the training of in-service operators to better appreciate and apply management techniques will be suggested.

CHAPTER II

THE ORIGIN, COMPONENTS AND QUALITY OF HEAVY FUEL OIL (HFO)

2.1.0 INTRODUCTION

This chapter will discuss the origin of heavy fuel oil (HFO). The term HFO and residual fuel will be used interchangeably. Selected refining processes which produce HFO will be discussed in an attempt to show the contributing factors to HFO quality. The undesirable components of HFO are also discussed.

The standardization of marine fuel specifications is a recent activity which involved several organizations. The agreed specification parameters and the acceptable upper limits for each grade of marine fuel will be highlighted. The relevant tests and their significance in ascertaining the actual content of fuel delivered, as well as their overall effect on engines are discussed.

Blended fuel and the future quality of HFO are introduced in this chapter. This is intended to draw attention to the problems associated with, and the necessary steps involved in blending fuel. The future quality of HFO will be of concern to operators; therefore, the decreasing quality of HFO is discussed with reference to the maximum specification parameters.

2.2.0 ORIGIN OF HEAVY FUEL OIL

Heavy fuel oil (HFO) used in slow speed diesel engines is exclusively refined from crude petroleum, usually referred to as crude oil or crude. Crude is normally found trapped between the upper or lower impervious rock known as caprock and bedrock respectively. The color of crude oils range from water-white to black (G.H. Clark 2/3).

Crude is composed of complex mixtures of hydrogen and carbon atoms from which the name hydrocarbon fuel is derived. There are other naturally occurring materials found in crude such as sulphur, nitrogen and oxygen compounds as well as water and trace amounts of organo-metallic compounds of vanadium, sodium, nickel and potassium (Shell 225).

The chemical structure of crude varies considerably. The amount of carbon atoms found in a molecule of crude with the associated hydrogen atoms primarily determines its molecular state at normal ambient temperature. Crude molecules with one to four carbon atoms exist as gases, five to sixteen carbon atoms are liquids and seventeen to one hundred carbon atoms are semi-solids or solids (Clark 2/3).

Crude oils are classified generally in three basic groups by their hydrocarbon chemical structure. The three groups are paraffin-base crude oils or alkanes, asphaltic-base crude oils (napthenes or cyclo-alkanes), and mixed-base crude oils or aromatics. These three basic groupings are directly associated with the type of products obtainable from the crude (Shell 234). See fig 2.1.

Residual fuel oils are "... products remaining from various refinery processes after all the distillate or lighter fractions have been removed. These residues are complex mixtures of aliphatic and aromatic hydrocarbons in varying proportions, depending upon the source of crude oils processed and the complexity of the refinery. Many of the residues are highly viscous-some which contain high molecular weight hydrocarbons are solid at ambient temperatures and may be used in the preparation of roadmaking materials and other bitumen products" (Shell 420).

To meet customers requirements, very high viscosity residues are blended with distillate products to decrease the viscosity and cut back on the solidifying elements as well. Thus, the term Blended HFO will also be encountered in the industry.

2.3.0 HEAVY FUEL OIL PRODUCTION

Crude oil refining is the process by which varying qualities of petroleum products are extracted. A typical modern refinery will incorporate several processes in the refining of crude. These processes include distillation, cracking, polymerization, reforming and alkylation. To improve the quality of the products, additional treatment such as isomerization, hydrofining, aromatics extraction, dewaxing, sulphur extraction and copper sweetening are used (Clark 3/4). See fig 2.2.

2.3.1 DISTILLATION, CRACKING AND BREAKING

Fractional distillation is the first phase of the refining process. This process makes use of the fact that different components of crude oil will boil at different temperatures. The higher the number of carbon atoms in a molecule, the higher the temperature required for it to boil.

The crude is heated to about 350-420 degrees Celsius (°C) and than introduced into the atmospheric distillation tower. Most of the lighter components of the crude evaporates and are than allowed to condense at various levels in the tower. The products are collected at these levels as distinct products commensurate with their carbon atom quantity in the hydrocarbon molecule. The atmospheric residue is reheated and used as feedstock to a vacuum distillation tower. It is in this tower where more heavier components used for producing lubricating oil, wax, and chemical feedstock are extracted from the residue.

The lighter components extracted in the vacuum tower are led to a catalytic cracker. In this cracker, a fluidized amorphous silica-aluminia catalyst is introduced into the preheated feedstock. This process produces a chemical reaction which further liberates lighter petroleum products from the feedstock (Shell 292). It is important to note that some small quantity of aluminium and silica known as catalyst fines or FCC fines remain in the residue. This residue is eventually drained out as slurry into the residual fuel.

The heavier residue from the vacuum tower could have a viscosity of about 5800 to 22000 cSt at 50°C. This feedstock is fed to a visbreaker where additional petroleum products are extracted and the residue viscosity reduced to about 3000 cSt at 50°C. The residue from the visbreaker, or in some cases directly from the vacuum tower, is blended with highly cracked aromatic gas oil to reduce the viscosity to about 380-560 cSt at 50°C (Clark 3/8).

It is this final residue that is known as **HFO, Residual fuel,** or **Blended HFO.** HFO at this stage has a higher concentration per volume of the natural compounds of vanadium, sodium, nitrogen, sulphur and other ash-forming compounds. Also present are aluminium and silica carry over from the catalytic cracker.

2.4.0 THE UNDESIRABLE COMPONENTS OF HFO

The quality of HFO varies considerably with type of crude and refining methods. The natural components found in crude as were identified are considerable enough to warrant special treatment prior to use. The quality of HFO will continue to decrease as more advanced methods of distillate extraction are used. The increased concentration of natural and catalyst fines will further decrease the combustion quality of HFO and certainly increase deposit formation in the combustion chamber and exhaust gas user equipment.

2.4.1 SULPHUR

Sulphur in crude oils varies from "... less than 0.2% by weight in some Pennsylvanian, Algerian and Russian crudes to over 6% by weight in some Mexican and Middle East crudes" (Shell 226). The increased pressure on refiners to extract more distillate from crude by catalytic cracking has given rise to sulphur content of up to 5% by volume in aromatic/asphaltic residual fuel.

The processes of hydrofining and desulphurization is being used for reducing sulphur content in products for land use. Stronger environmental regulations have made the latter processes mandatory. It is possible to desulphurize fuels for marine use. However, the process is costly and there is no requirement to limit sulphur content in marine fuels.

Sulphur in residual fuel is detrimental to diesel engines and exhaust gas user equipment. It promotes corrosive wear of piston rings, liners, waste heat boilers, and increases deposit formation on piston ring zones.

2.4.2 VANADIUM AND SODIUM

Vanadium is increasingly being isolated from feedstock used in catalytic cracker. Along with iron and nickel, they will reduce catalyst activity in the cracker. To avoid this problem, a high degree of distillation is employed. Consequently, substantial portions of these elements are entrained in the residue.

Vanadium in oil soluble form is a troublesome constituent of ash in combustion bi-products. There is no economical process for removing vanadium from residual fuels. Vanadium content in residual fuel seldom exceeds 200 parts per million (ppm). However, Venezuelan crude used in producing HFO may have up to 600 ppm of vanadium (W. D. Ewart 10).

W.D. Ewart asserts that "the most serious operating problems occur when vanadium combines with sodium and forms ashes which have melting temperatures ranging from 550°C to 900°C depending on the relative proportions. Melted sodium vanadium ash will directly corrode steel. The situation becomes even more critical when the ash deposits as a plastic layer on hot exhaust valves and valve seats. The valve action hammers out the layer which then flakes and provides passages for wire drawing of hot gases and these than damage valves and seats" (Ewart 10).

Sodium will also react with vanadium and oxygen to form oxides which are highly corrosive at high temperatures. These oxides would leave deposits on turbocharger nozzles and blades. Vanadium will also serve as a catalyst in the formation of sulphuric acid (Clark 4/10).

2.4.3 ALUMINIUM AND SILICA

The catalyst used in the cracker is a zeolite matrix made of alumina and silica. These catalyst fines which are elements of this matrix exist as aluminium trioxide, alumina and silicon dioxide. Refineries have used efficient cyclone separators to recover this expensive catalyst but have not been 100% successful.

Aluminium and silica entrained in residual fuel are highly abrasive. If they are not eliminated or minimized in the onboard treatment process, they could affect injection equipment adversely and increase cylinder liner/piston ring wear rate.

The International Standard Organization (ISO) has issued a specification which sets a limit on aluminium content in catalyst fines to 30 ppm. Silicon content limit proved very impracticable as contaminants such as sand may enter the fuel after the refinery, thereby increasing the apparent silica content. However, it is generally argued that the 30 ppm limit on aluminium does not by the proportionality of the matrix composition provide an overall limit of 180 ppm of catalyst fines in residual fuels. Test methods will have to be developed to account for the silicon content or the "Total Catylist Content" (H. Breyer 31).

2.4.4 COPPER, ZINC, IRON, NICKEL AND WATER

These four elements are naturally found in relatively small quantities in crude and vary with the type of crude. Their concentration in crude and eventually HFO is very minute. They are easily removed by onboard treatment facilities. Their presence in HFO have not been of major concern due to their average quantity of less than 25 ppm.

Water is certainly an undesirable component of HFO. Salt water in particular is corrosive and increases the ash-forming constituents in fuel. Normal water content as found in delivered fuels can be removed by settling and centrifuging.

2.5.0 THE AWARENESS OF HFO QUALITY

The quality of HFO and marine bunkers in general was never questioned prior to the 1973-1974 fuel crisis. Ship operators were concerned with the viscosity of 180 cSt as the upper limit for fuel specification for slow speed diesel engines. After the onset of the 1973-1974 fuel crisis, refiners began employing more advanced methods of product extraction from crude as was discussed earlier.

One noticeable immediate change in the fuel quality was an increasing availability of more viscous fuels. Thermal and catalytic cracking brought along more asphaltenes and incompatibility of certain fuels. These two elements resulted in increased sludge and sediment accumulation in onboard storage tanks. As the viscosity increased, so did the specific gravity (density). The principle of separation and maintaining a water seal in separators became fragile as fuel density approached 0.990 g/ml.

Economic pressure and the gradual but steady isolation of the less efficient steam propulsion plants, coupled with the proliferation of the more efficient slow speed diesel engine, forced ship operators to accept what was available from the refiners. It was also apparent that the higher heating requirement for the marketed grades of HFO was reaching if not exceeding the designed capability of the fuel heating systems. Increased fouling of heaters was also prevalent. Unfortunately, the realization by ship operators of the detrimental consequences of the undesirable components of HFO came later as operational problems became pronounced.

By 1977, it was apparent to engine builders and ship operators that there was a dire need for a standard specification for marine fuels. W.D. Ewart highlights the events of the 1978 meeting held under the auspices of the British Standards Institution (BSI) as one which saw an agreement between ship owners, engine builders and oil suppliers on the need for marine fuel specification. A committee was formed to address the issue with the relevant terms of reference (Ewart 12).

The problem of poor quality fuel was becoming more and more acute by 1980. The International Chamber of Shipping (ICS) unilaterally issued a "Bunker Delivery Note" in September of 1980. See fig. 2.3. The intent was to provide further knowledge for ship operators as to the quality of the fuel received. Although the latter was widely rejected by the oil industry, ICS and the Baltic International Maritime Charterer's Organization (BIMCO) issued the "Bunker Fuel Quality Clause for Time Charters". Excerpts from the clause reads as follow:

"1. The Charterers shall provide fuels suitable to the Vessel to enable the main propulsion and auxiliary machinery to operate efficiently and without harmful effects, normal wear and tear excepted.

2. Fuels supplied shall conform to specifications mutually agreed between Owners and Charterers. If fuels are blended the equipment and the components used shall be warranted to provide a stable fuel suitable for use after normal storage onboard the vessel when bunkered in empty tanks. A Bunker Delivery Note shall be presented to the Vessel at the time of delivery of fuels, specifying the quantity and the agreed specification of the fuels...." (Ewart 55).

It is encouraging to note that a substantial number of bunker suppliers are complying to this clause on a voluntary basis.

To date, there are several marine fuel standards and classifications issued by recognized authoritative organizations. However, these defined parameters serve only as a guide to the inherent quality of the fuel. Quality assurance is a much needed aspect in marine bunkers. Delineating what is acceptable and unacceptable technically and environmentally is an awesome task, but efforts should continue towards this end.

2.6.0 MARINE FUEL SPECIFICATION

Marine fuel specifications have developed as a means to effectively communicate the customer's requirements to the fuel supplier. There have been several parameters developed to assure that the quality of the fuel is delivered in good faith as ordered. To remove any doubt as to the fuel supplied being according to specification, samples of the fuel are collected during bunkering and sent to an independent laboratory for analysis. Veritas Fuel Quality Testing Programme (VFQTP-DNV) and Fuel Oil Bunker Analysis Services (FOBAS-Lloyds) are well established fuel testing programs which provide expert analysis and suggestions on the quality of fuels.

The American Society for Testing and Materials (ASTM) has issued standards for diesel fuel oils since 1948. There have been several revisions of the standards. The parameters and range of given grades have been very broad and give no indication for their application to large marine diesel engines fuels.

In 1982, BSI issued specifications for varying grades of marine fuels. This was the first real attempt to associate fuel quality with the varying grades and parameters of marine bunker. The new specification was called "BS-MA100". See table II-1.

The International Council on Combustion Engines (CIMAC), in consultation with diesel engine manufacturers, began work on residual fuel standards. "CIMAC-Recommendations Regarding Requirements for Residual Fuels for Diesel Engines (as bunkered)" was published in December 1985.

The ISO, in conjunction with all parties concerned, developed an international standard for marine fuels (ISO 8217). See table II-2. The new standard was published on April 15, 1987. It is generally agreed that this standard will be used worldwide, thereby eliminating specification disputes between suppliers and buyers.

Fuel specification for the ship operator today is easier by use of these established standards, particularly the ISO standard. The parameters as discussed below cover the essential elements of fuel quality of which ship operators should be aware.

The density of fuel is quoted at 15°C and stated in g/ml. The current upper limit has been established at 0.991. Although separators have been developed to handle fuel densities up to 1.050 g/ml, the extent to which higher density fuel is accepted will depend on shipowners willingness to invest in new equipment and new construction.

The viscosity of fuel is quoted as kinematic viscosity at 80°C. The upper limit is 130 cSt at 80°C. The new ISO standard recommends viscosity to be quoted at 100°C. In this case, the upper limit would be 55 cSt at 100°C. The extent to which higher viscosity fuel will be accepted will depend on the heating capability of shipboard equipment as well as the amount of energy required to heat the fuel.

Conradson carbon residue is stated as a percentage of the fuel mass. It indicates the tendency of the fuel to form carbonaceous deposits when burnt. Conradson carbon residue for HFO is relatively high, in particular for cracked residual fuel. The maximum of 22% for heavier grades has not been experienced on board as yet. This maximum value sets a limit for future fuel as quality decreases.

Flash point is a broad indication of the temperature at which fuel gives off vapor to form a flammable mixture with air at atmospheric condition. Most HFO's are non-volatile; however, the amount of cutter stock used in the blend may decrease the flash point considerably irrespective of the viscosity. Establishing the minimum temperature of 60°C assures that the fuel can be safely handled and stored aboard under normal conditions.

Water content is stated as a percentage of the fuel volume The limit of 1% is a widely accepted value. Most fuels do not reach this limit except in cases of accidental contamination. Fuel with 1% water content or slightly higher can be handled by shipboard treatment facilities.

Pour point and **cloud point** are parameters which provide the operator with additional information for storage and handling of the fuel. The pour point of HFO is stated at an upper value of 30°C. The actual temperature at which interlacing crystals prevent the oil from flowing is 3 degrees below the pour point.

Cloud point is gaining prominence as a standard parameter due to the presence of paraffin wax in residual fuels. This parameter defines the temperature at which wax begins to form on the fuel. The cloud point is higher than the pour point.

Sulphur content is quoted as the maximum acceptable percentage of the fuel mass. The upper limit is currently established at 5%. This represents a very high sulphur content which is undesirable in the presence of other contaminants.

Vanadium content is established at a maximum value of 600 ppm. This measurement is the amount in milligrams of vanadium with respect to the fuel mass in kilograms. This upper limit, as was expressed earlier, is found in residual fuel derived from cracked Venezuelan crude. A high vanadium and sulphur content would cause high corrosive wear in diesel engines operating at reduced loads and low jacket cooling water temperature.

Ash content of 0.2% is the maximum acceptable percentage of the fuel mass. This parameter is essential as it defines the quantity of abrasive ash contaminants. These contaminants are most often soluble organometallic compounds which cannot be removed by the shipboard treatment facility.

Aluminium content is established at a maximum of 30 ppm (mg/kg) as was discussed in section 2.4.3. However, there is no standardized test method for determining the aluminium content in fuel.

Total existing sediment is a relatively new parameter being discussed for inclusion in the ISO specification. This parameter would attempt to indicate stability and compatibility of fuel. These two quality indicators will determine the degree of stratification and sludge formation tendency of marine fuels.

Ignition quality of residual fuel is currently under review for inclusion in fuel specifications. The ignition, combustion, and burnability properties of residual fuel will decrease along with the others. The development of test methods and a specification to this respect is very necessary.

Recent studies have revealed that the Calculated Carbon Aromaticity Index (CCAI) gives a good indication of the ignition quality of fuel. The CCAI works on a scale from about 750 to 950 for HFO. The higher the index, the lower is the ignition quality. The carbon aromaticity is a function of the density and viscosity of the fuel. Thus, the below formula has been derived to determine CCAI.

$$CCAI = D - 81 - 141 \log \log(V + 0.85)$$

where D = density kg/cubic meter at 15°C

V = viscosity mm square/sec at 50°C

(Det Norske Veritas 17).

2.7.0 HFO TESTING AND SIGNIFICANCE

Marine fuel testing is the effective means of assuring fuel quality. Fuel testing also establishes the actual quantity of components and the characteristics of fuel delivered. Fuel testing as carried out by the refiners is credible. However, the transport mechanism of fuel from the refiners to the ship may take different stages and transport systems. It is therefore essential for the ship operator to obtain on line samples during bunkering. These samples should be taken and sealed in the presence of the supplier and dispatched as early as possible to an independent fuel testing laboratory for analysis.

There are many tests which can be carried out on fuel samples. These various tests verify all the parameters as described in the previous section on marine fuel specification. Tests are also carried out to establish the calorific value, asphaltene content, diesel index and aniline point.

The various test methods for some of the criteria have been standardized and agreed upon by ASTM, the Institute of Petroleum (IP), BSI and ISO. It is certain that the ISO will agree on the test methods for all fuel test criteria to complete the standardization of marine fuel quality and quality control.

For the ship operator, not all of these tests are necessary. Some tests are valuable for refiners and engine manufacturers and others are for the ship operator. Those tests that are relevant for the ship operator will be discussed.

2.7.1 THE SIGNIFICANCE OF SPECIFIC GRAVITY (DENSITY) AND VISCOSITY TESTS

The specific gravity of the fuel delivered to the vessel should be confirmed. This information is relevant in determining the gravity disc size versus purification temperature. Operators rely on the accuracy of this parameter to adjust the purifiers. An error in quoting the right value could lead to inefficient adjustment of the purifier. The operator relies on the specific gravity value for calculation of fuel consumption and fuel remaining on board.

The viscosity is relevant to the ship operator in determining the purification and injection temperatures. The major manufacturers of purifiers have produced tables which relate viscosity and temperature to the maximum and optimum throughput for various models of purifiers. The viscosity of the fuel is also necessary to determine the level of heating required in storage tanks, thereby avoiding pumpability problems.

Although automatic viscosity controllers are used extensively in the industry, operators should be aware of the practical implications of maintaining the right injection viscosity. Variation in injection viscosity could lead to fluctuation in the already high dynamic pressure in the injection pumps, as well as inconsistent fuel spray and droplet pattern in the combustion chamber.

The operator should also be aware that the pressure at which fuel is injected affects the viscosity necessary for good atomization. Therefore, one should check the

viscosity-temperature-pressure relationship curves to obtain the true value of the required injection viscosity.

2.7.2 THE SIGNIFICANCE OF SULPHUR, VANADIUM, ASH CONTENT AND CALORIFIC VALUE

Sulphur content is an essential parameter for the operator. The operator should be alert to correlate a high sulphur content of more than 3.5% with a high vanadium content in excess of 300 ppm. These two undesirable constituents of HFO, and in particular, at high concentration should certainly drive the operator to take recommended actions without hesitation.

Ash content is a good indication for the operator to use in adjusting the final throughput and purification equipment use. The ash content is the total result of soluble and insoluble particles. The aluminium content should be viewed critically as this and other catalyst fines are the principal constituents of insoluble ash.

The calorific value is not a necessary test result for the operator. The quoted value on the delivery note will not differ considerably from test results. For thermodynamic calculations of efficiency and power stated values are acceptable. The net specific energy can be calculated from the below formula:

$$W = 55.5 - 14.4d - 0.32S$$

W = net specific energy (MJ/kg)

d = fuel density at 15°C (kg/l)

S = proportion by mass of sulphur (%/100)

(Veritas 17).

2.7.3 CONRADSON CARBON RESIDUE, ASPHALTENE AND WATER CONTENT TESTS

Conradson carbon residue and asphaltene content are two tests which primarily give indications of the combustion quality of the fuel. A high value of conradson carbon residue should concern the operator as the asphaltene content is about 75% of the carbon content. This will increase carbonaceous deposit accumulation in crosshead engine buffer spaces. This is practically unavoidable in loop scavenging engines with relatively low scavenge air pressure.

Too high asphaltene content on the other hand could cause delay ignition of fuel particles. Such delay could result in scavenge belt fire, and solidify carbonaceous deposits in cylinder liner scavenge air ports and piston ring grooves. This problem is not prevalent in newer high air charged and uniflow scavenging engines. However, carbonaceous deposits accumulation in the buffer space could occur and more frequent cleaning may be necessary.

Water content test is a plus but not critical. The normal content is below 1% by volume. Secondly, excess water can easily be detected and remedied on board.

2.7.4 STABILITY AND COMPATIBILITY TESTS

The stability of fuel should be tested and suppliers must guarantee adequate reserve stability. Where blended fuel is delivered, the stability of the product should insure that stratification according to the blended components

does not occur. The Shell Hot Filtration Test (SHFT) is

very useful in determining the cleanliness and stability of fuel. The simulated ageing method used prior to SHFT provides realistic information as to the fuel reserve stability as measured by the amount of deposits.

The compatibility test is a relevant measure of two fuel products to mix without the formation of large amounts of sludge. Incompatible fuels have different hydrocarbon groups which would cause the asphaltenes to settle out when they are mixed. This test provides valuable knowledge for storage of fuels.

2.7.5 ON BOARD TESTING OF HFO

There are test kits available for testing the essential parameters of fuel. Although these kits are not prominent, it is only a matter of time before they become a standard complement for the operator.

Compatibility tests can also be carried out with these kits. This will prove to be a viable component of the kit as the problem of incompatibility of fuel from different bunkering points becomes pronounced. Fuel sampling points should be placed near the bunker intake point, before and after centrifuging equipment, and just before the engine.

These kits provide fairly good results, but should only complement tests done by established laboratories.

2.8.0 BLENDED HFO

Blending fuel is a practice which requires appropriate knowledge and equipment. Refiners and suppliers of

bunkers usually blend distillate and heavy residue to arrive at the requested viscosity. Quite often, this process is done by the supplier when alongside or when pumping aboard. Most HFO supplied today are blended fuels. Straight run residual fuel is becoming increasingly scarce.

Shipboard blending of HFO and marine diesel oil to obtain an intermediate grade for auxiliary engines has been practised with mixed results.

It is important to note that in order to avoid incompatibility due to blending, the following measures should be carried out. Cracked distillate with cracked residue would make a better blend as well as straight-run distillates with straight-run residues. To improve the blend even further, products from the same crude and refinery will provide a more stable blend.

Compatibility tests of the two products to be blended should be carried out. G.W. Clarke argues that incompatibility of the two components will result "... in the separating out of heavy asphaltene components, resins and wax. This has resulted in an abnormal discharge of sludge from centrifuges (in some cases blocked fuel lines and filters) and serious combustion problems"(Clark 4/18).

Currently ship operators are experiencing another phenomena of blending. Very hot HFO (110°C or more) returning to the atmospheric mixing tank from the injection system quite often tend to separate into light and heavy phases. Gas formation in the standpipe would force the light phase out through the vent pipe. Samples

collected from this spillover has been confirmed to be light distillate product.

To reduce the problem of incompatibility of blended HFO, operators should minimize the number of bunkering points when possible. The onboard quantity should be consumed to a safe minimum before taking fresh bunkers on existing vessels with a single set of fuel storage tanks.

2.9.0 THE FUTURE OF HFO

The quality of HFO will continue to deteriorate. Engine manufacturers are testing engines capable of burning BS-MA100 M8 to M9 range fuel with respectable results. The level of undesirables present in HFO will approach the upper limits as quoted in the specifications.

Centrifuging has advanced to accommodate fuel with specific gravity greater than 1.000 g/ml. The one fuel ship is becoming very much a reality. Therefore, to keep pace with this trend, the ship operator needs to understand more about fuel and how to deal with it.

ANNEX—A

Fig. 2.1 "Percentage composition of typical crude oil fractions determined by atmospheric distillation."

Fig. 2.2 Petroleum Products Refining Layout.

Fig. 2.3 Recommended Bunker Delivery Note

Table II-1 BS MA-100 Marine Fuel Specification

Table II-2 ISO Marine Fuel Standard (ISO 8217)

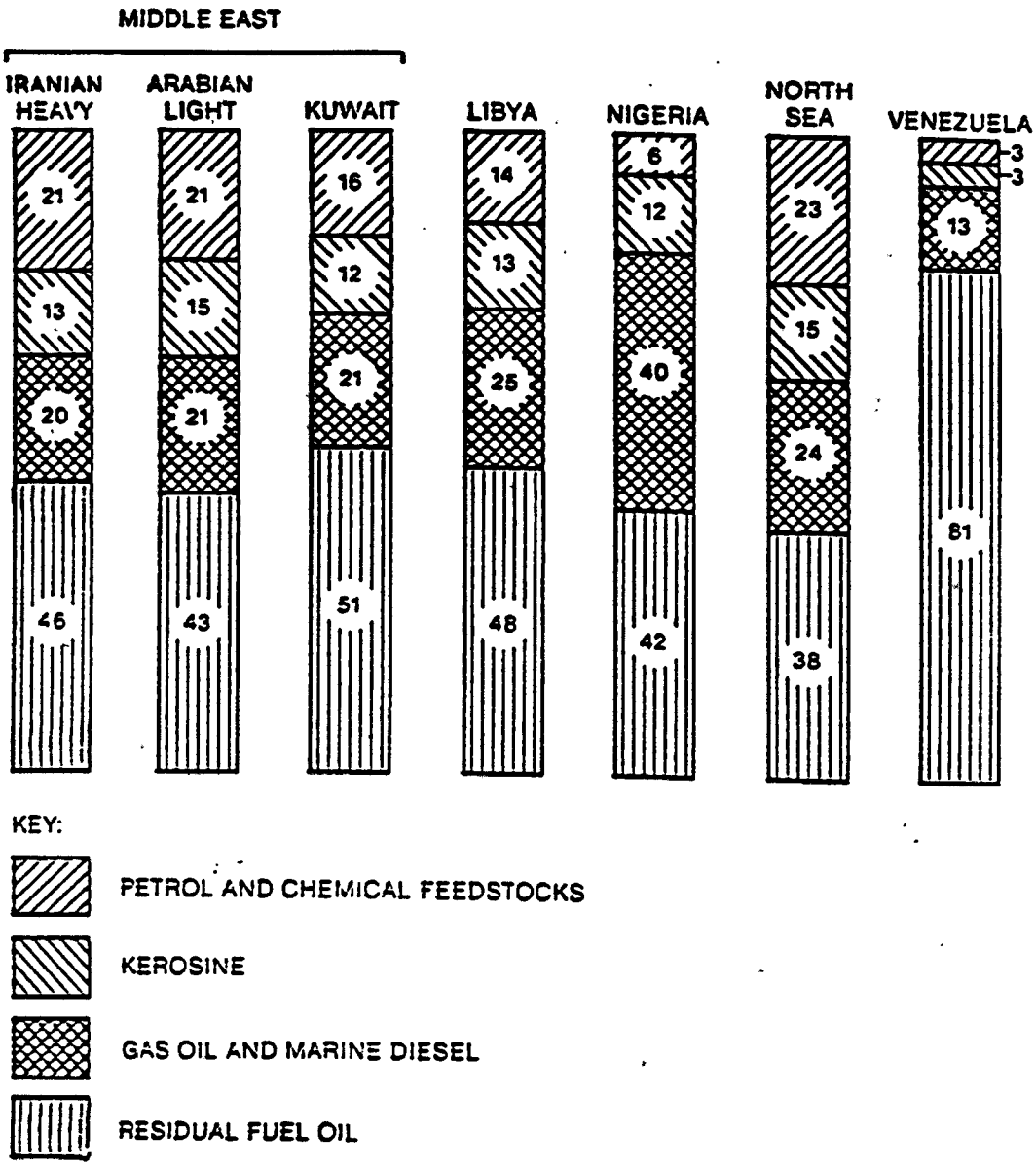


Fig. 2.1 "Percentage composition of typical crude oil fractions determined by atmospheric distillation."

Source: George H. Clark. Industrial and Marine Fuels Reference Book.

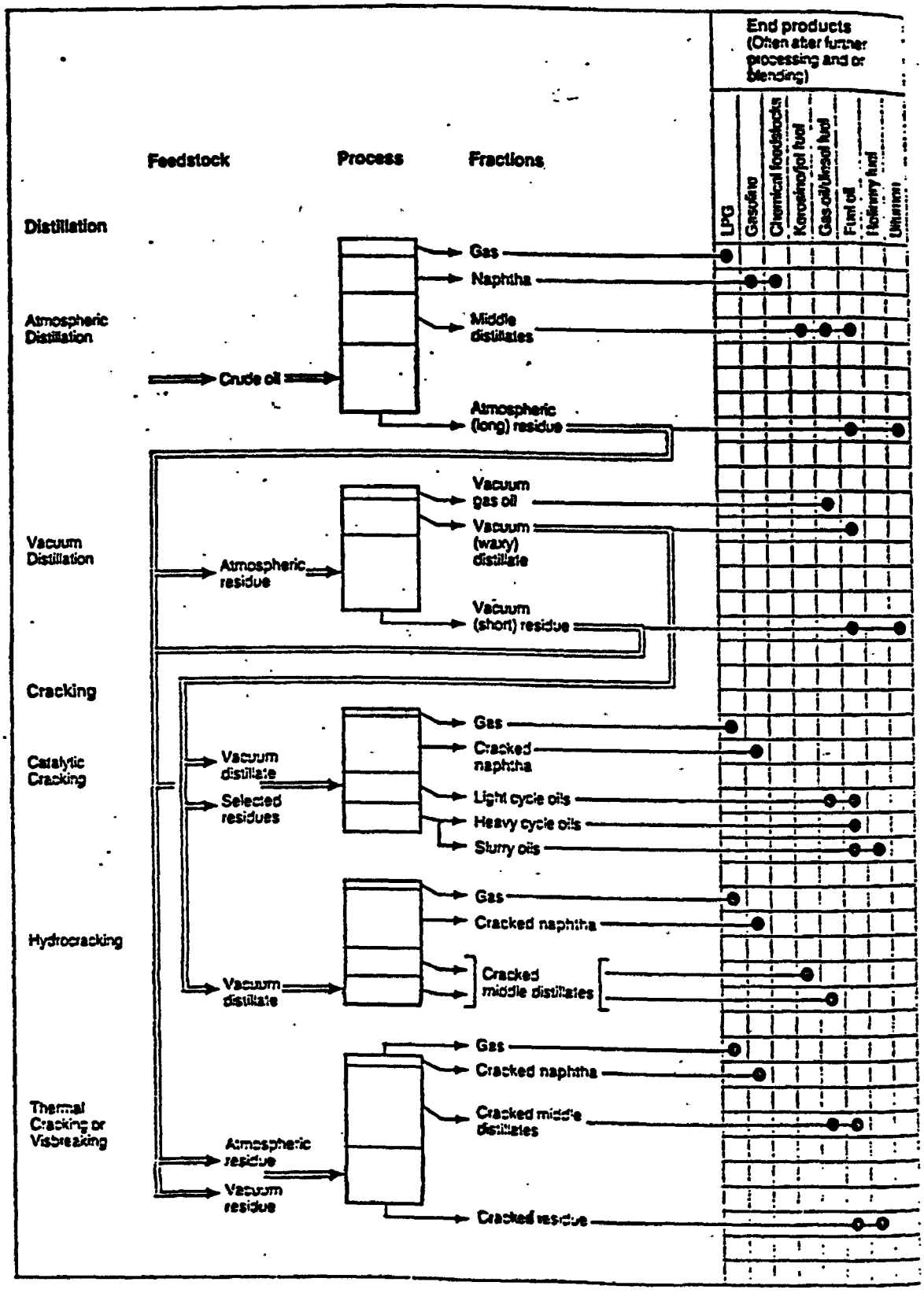


Fig. 2.2 Petroleum Products Refining Layout.
(Courtesy of Shell Int.).

INTERNATIONAL CHAMBER OF SHIPPING

RECOMMENDED BUNKER DELIVERY NOTE

NAME OF VESSEL: _____ (PORT)

Product name or general designation	
Quantity in tonnes	
Volumetric Quantity (m^3)	
Temperature of Product (°C)	

Density at 15°C (kg/litre)	
Kinematic Viscosity (cSt) at corresponding temperature (°C)	
Flash Point (P–M) Closed Cup (°C)	
Pour Point (°C)	
Conradson Carbon Residue (percentage by mass)	
Sediment (percentage by mass)	
Water Content (percentage by volume)	
Cetane Index (distillate fuels only)	
Sulphur (percentage by mass)	
Vanadium (mg/kg)	

Note: Specific energy (calorific value) (MJ/kg) can be calculated from the known density and sulphur contents in the formulae quoted in BS 2869 Amendment 2 "Petroleum Fuels for Oil Engines and Burners".

Bunker Supplier: _____

Signature of Suppliers' Representative or Agent: _____

Date of Delivery: _____

Fig. 2.3 Recommended Bunker Delivery Note (Courtesy of ICS).

Properties of marine fuels British Standard BS MA100:1982

Property	Class M1	Class M2	Class M3	Class M4	Class M5	Class M6	Class M7	Class M8	Class M9	Class M10	Class M11	Class M12
Density at 15°C, g/ml, max		0.9000	0.9200	0.9910	0.9910	0.9910	0.9910	0.9910	0.9910	..		
Viscosity, kinematic, at 40°C, cSt*, min	1.50	–	–	..	–	–	–	–	..	..	..	
max	5.50	11.00	14.00	.	.	..	.	.	..	.	.	
Viscosity, kinematic, at 80°C, cSt*, max	..	0.25	2.5	.	..	.	.	–	..	.	.	
Carbon residue, Ramsbottom on 10% residue, %(m/m), max	0.20	–	–	–	..	–	..	..	..	..	..	
Carbon residue, Conradson, % (m/m), max	.	.		12.0	14.0	20.0	22.0	22.0	22.0		.	
Flash point, closed, Pensky-Martens, °C, min	43.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
Water Content, % (V/V), max	0.05	0.25	0.30	0.50	0.80	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Sediment by extraction, % (m/m), max	0.01	0.02	–	–	–	–	–	–	–	–	–	–
Ash, % (m/m), max	0.01	0.01	0.05	0.10	0.10	0.15	0.20	0.20	0.20	0.20	0.20	0.20
Sulphur content, % (m/m), max	1.00	2.00	2.00	3.50	4.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Cloud point, °C, max	−16	..	–	–	–	..	–	.	–	–	–	–
Pour point, upper†, °C, max (1 December to 31 March)	–	0	0	24	30	30	30	30	30	30	30	30
(1 April to 30 November)	–	6	6	24	30	30	30	30	30	30	30	30
Vanadium content, mg/kg, as V, max	–	..	100	250	350	500	600	600	600	600	600	600

* 1 cSt = 1 mm²/s.
† The word 'upper' does not apply to classes M2 and M3.

Table II-1 BS MA-100 Marine Fuel Specification

Source: Shell Int. Trading Company

ISO 8217 – Petroleum Products – Fuels (Class F) – Specifications of Marine Fuels

ISO 8217 was issued in 1987. It covers 19 different categories of fuel – four distillates, ten residual fuels with a density limit of 991 Kg/m³ and five residual fuels with no density limit.

Table 14.2 lists the ISO limits for those inspection properties covered by existing test methods. In preparing the specification for fuels containing residual material, the ISO recognised that further inspection properties were highly desirable but that there were no internationally agreed test methods in existence. These properties are (a) existent sediment; (b) ignition quality, and (c) abrasive particulates.

Table 14.2a
International Standard ISO 8217
Petroleum products – Fuels (Class F) – Specifications of marine fuels – Requirements for marine distillate fuels

Characteristics	Test method	Limit	Designation ISO-F- DMX	DMA	DMB	DMC
Density at 15°C, kg/m³	ISO 3675	max	–[a]	890	900	920
Kinematic viscosity at 40°C, cSt	ISO3104	min	1.40	1.50	–	–
		max	5.50	6.00	11.0	14.0
Flash point, °C	ISO 2719	min	43	60	60	60
Pour point[b] Winter quality	ISO3016	max	–	–6	0	0
(upper) °C Summer quality		max		0	6	6
Cloud point, °C	ISO3015	max	–16[c]	–	–	–
Carbon residue, Ramsbottom % (m/m) on 10% residue	ISO 4262	max	0.20	0.20	–	–
Carbon residue, Ramsbottom % (m/m)	ISO 4262	max	–	–	0.25	2.50
Carbon residue, Conradson % (m/m)	ISO 6615[d]	max	0.14	0.14	0.25	3.0
Ash % (m/m)	ISO 6245	max	0.01	0.01	0.01	0.05
Sediment by extraction, % (m/m)	ISO 3735	max	–	–	0.07	–
Water, % (V/V)	ISO 3733	max	–	–	0.3	0.3
Cetane number	ISO 5165	min	45	40	35	–
Visual inspection	[e]	–	Clear	Clear	–	–
Sulphur, % (m/m)	[f]	max	1.0	1.5	2.0	2.0
Vanadium, mg/kg	[g]	max	–	–	–	100

[a] In some countries there will be a maximum limit.
[b] Purchasers should ensure that this pour point is suitable for the equipment on board, especially if the vessel is operating in both the Northern and Southern hemispheres.
[c] This fuel is suitable for use at ambient temperatures down to –15°C without heating fuel.
[d] Test method ISO 6615 is to be used only when test method ISO 4262 is not available.
[e] Inspect in good light at temperature between 10°C and 25°C. Sample shall be clear and bright.
[f] The sulphur content shall be determined in accordance with ISO 8754. At present at the state of draft.
[g] An international standard is being prepared. Pending its completion, vanadium shall be determined by the method DIN 51 790, Part 2 (July 1978) (published by Deutsches Institut für Normung, Berlin).

Table 14.2b
International Standard ISO 8217
Petroleum products – Fuels (Class F) – Specifications of marine fuels – Requirements for marine residual fuels

Characteristics	Test method	Limit	Designation ISO-F RMA 10	RMB 10	RMC 10	RMD 15	RME 25	RMF 25	RMG 35	RMH 35	RMK 35	RML 35	RMH 45	RMK 45	RML 45	RMH 55	RML 55
Density at 15°C, kg/m³	ISO 3675	max	975	991	991	991	991	991	991	991	–	–	991	–	–	991	–
Kinematic viscosity at 100°C, cSt	ISO 3104	max	10.0	10.0	10.0	15.0	25.0	25.0	35.0	35.0	35.0	35.0	45.0	45.0	45.0	55.0	55.0
Flash point, °C	ISO 2719	min	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
Pour point[a] (upper) °C winter quality	ISO 3016	max	0	24	24	30	30	30	30	30	30	30	30	30	30	30	30
summer quality		max	6	24	24	30	30	30	30	30	30	30	30	30	30	30	30
Carbon residue Conradson % (m/m)	ISO 6615	max	10	10	14	14	15	20	18	22	22	–	22	22	–	22	–
Ash, % (m/m)	ISO 6245	max	0.10	0.10	0.10	0.10	0.10	0.15	0.15	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Water, % (V/V)	ISO 3733	max	0.50	0.50	0.50	0.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Sulphur, % (m/m)	[b]	max	3.5	3.5	3.5	4.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Vanadium, mg/kg	[c]	max	150	150	300	350	200	500	300	600	600	600	600	600	600	600	600

[a] Purchasers should ensure that this pour point is suitable for the equipment on board, especially if the vessel is operating in both the Northern and Southern hemispheres.
[b] The sulphur content shall be determined in accordance with ISO 8754. At present at the state of draft.
[c] An international standard is being prepared. Pending its completion, vanadium shall be determined by the method DIN 51 790, Part 2 (July 1978) (published by Deutsches Institut für Normung, Berlin).

Table II-2 ISO Marine Fuel Standard (ISO 8217)

CHAPTER III

HEAVY FUEL OIL STORAGE, TRANSFER AND TREATMENT

3.1.0 INTRODUCTION

HFO storage, transfer and treatment are inter-related aspects of the fuel management concept. They are interdependent and complementary to each other. Adequate knowledge of the features involved in managing these aspects is paramount.

In view of the latter, this chapter will address the problems associated with shipboard storage and transfer of HFO. The optimum plant configuration relative to the latter will be discussed.

Some operators ignore or are unaware of the benefits associated with the specific design features of settling and service tanks. There is also the tendency to misuse the system primarily for convenience. This chapter will reiterate and probe into the inherent benefits of the design and operational aspects of these tanks. The varying quality and related contaminants of HFO will be discussed with regards to the service and settling tanks.

There have been substantial developments in centrifuging technology. The conventional and new generation centrifuging systems will be discussed. The design features and optimum operational application of this

equipment with respect to fuel quality will also be discussed.

Homogenisers, filters and fuel additives have been used in the treatment of HFO. Their individual merits and demerits will be examined. The optimum use of the respective items will be explored where found acceptable.

3.2.0 THE STORAGE OF HFO

The storage of HFO begins by the initial planning of where and how much of the HFO to be received would be distributed on board. A well planned storage program should include consideration of the quantity, quality and trading route of the vessel amongst others. The plan should be concluded well in advance of the commencement of bunkering.

Fuel with a high pour point and high viscosity may form wax when allowed to cool below the pour point. The wax could insulate the heating coils rendering them incapable of raising the temperature to the pumpability range.

Particular attention should be given to the quality of HFO for vessels trading in waters with temperatures less than the pour point of the fuel. Vessels fitted with deep forward fuel tanks are very prone to this problem. Conventional operational practice of closing off the heating supply to deep forward tanks and supplying heat a day or two prior to transfer could prove disastrous. Operators should at all times maintain the temperature of the fuel above its pour point.

Newer engines are capable of burning some of the lowest grade fuel available today. Centrifuging technology has advanced where the density of fuel is no longer the limiting parameter. Therefore, it is suggested that vessels be equipped with, e.g., four small deep fuel storage tanks as compared with two large tanks. Double bottom storage tanks should be avoided where possible.

Where tanks are located forward and steam heating is used, the heating steam line should be independent of the deck machinery steam supply. Proper insulation of the heating line should be carried out.

The considerations discussed will help the operator avoid incompatibility of different HFOs. Problems associated with the use of the fuel can be convincingly traced to the origin of the bunkers. The heating system for the deep tanks can be operated more efficiently to avoid wax formation in storage.

3.3.0 THE TRANSFER OF HFO

The transfer system of HFO between storage tanks and to settling tanks has not been of concern to the operators. This attitude can be attributed to the initial system design to accommodate fuel at higher viscosity than would be found in other sections of the fuel system. The latter statement does not imply that the system has been completely troublefree.

The transfer piping system for HFO should have a self draining facility, trace heating and lagging. A positive displacement pump should be used to avoid the

emulsification of water and fuel. Where high pour point fuel is used, air or steam blow through facilities for the transfer line should be considered (CIMAC 11).

3.3.1 HFO SETTLING TANK

Settling tank, by definition, allows for water and heavy contaminants in the fuel to accumulate at the bottom of the tank. However, the effectiveness of this process depends on several variables.

The settling process depends on the relative density of separating elements, viscosity of the fuel, the residence time of the fuel in the tank, the height of the tank, the temperature and temperature fluctuation of the fuel, the surface area of the tank, the configuration of the tank bottom and associated piping.

The residence time of the fuel in the tank can be increased during the design phase by using two settling tanks with a capacity of 24 hours. The tanks should be switched over on a daily basis to prevent ageing. This arrangement certainly allows for new bunkers to be independently tested through the treatment system. In addition, tanks can be cleaned and bad fuel retransferred without interrupting normal operation.

The height of the settling tank should be limited thereby reducing the time for contaminants to travel downwards through the fuel. A lower tank height will decrease the number of thermal stratifications in the tank as well.

The temperature of the fuel is important for settling. A recommended temperature of 70°C will provide a large relative density difference between fuel and water as well as contaminants. However, prolonged storage of fuel at high temperatures should be avoided, thus preventing the onset of ageing and stratification in blended fuel. Temperature fluctuations should be kept to a minimum, thereby, maintaining a constant relative density throughout the tank. Where feasible, the tank should be insulated.

The surface area of the tank would definitely increase if the height of the tank is kept as low as practicable. To reduce free surface movement and turbulence in the tank, wash bulkheads should be installed. Perforated plates should be placed above the bottom of the tank. This would prevent sediment movement when sloshing occurs or when fuel is pumped into the tank (VERITAS 56).

The tank bottom should be sloped to improve the draining of water and sludge from the bottom. Fuel entering the tank should be led close to the bottom of the tank, preferably above the perforated plate, where installed, and away from suction lines. Suction lines should be placed well above the tank bottom and perforated plate. Drainage lines should be placed at the bottom to allow for complete draining of the tank when necessary (VERITAS 56).

Some operators perceive the settling tank as only a transit point for fuel. They argue that sediment and water separation in the settling tank is insignificant as compared to the quantity remove by the centrifuging process. It is dangerous to accept this argument.

Operators should realize that in conjunction with the design and operational considerations suggested in this section, excess water contamination of the fuel in storage can best be detected in the settling tank.

3.3.2 SERVICE TANK

The service tank provides a buffer between the fuel treatment section and the pre-injection section of the plant. The service tank assures a limited reserve of clean fuel in case the fuel treatment plant breaks down.

To complement the flexible fuel treatment system, two service tanks would be advantageous. Poor quality fuel as bunkered or due to centrifuging deficiency can be retransferred without interrupting engine operation.

The capacity of the service tanks should be calculated to keep the engine running if and when a single settling tank system has to be emptied and refilled. The down time for maintaining the centrifuging plant should also be considered. In no case should the capacity be less than 12 hours supply.

The service tank should not be used as a high temperature heater. Temperature in excess of 85°C would promote stratification, gasing and thermal instability (sludge formation). Hot fuel returning from the injection system should not be returned to the service tank. Instead, hot fuel should be led to the mixing or buffer tank.

To improve the effectiveness of the service tank, CIMAC recommends the following:

"1. Drain a specified quantity of fuel automatically at regular intervals, and return it to the settling tank. This could be done at short intervals, by means of a separate pump and pipe connection, or by draining into the double bottom tank, the contents of which is then pumped to the settling tank by means of the transfer pump.

2. Recentrifuge the service tank contents regularly drawing the fuel from the bottom of the service tank. This can be done every time the vessel is in port for marine installations and every night or every week-end in power stations, or it can be done continuously with a small portion of the fuel. To that end a flow control valve should replace the change-over valve on the suction side of the oil feed pump" (CIMAC 12).

The basic design of the service tank is similar to that of the settling tank. In addition, the service tank overflow piping to the settling tank should lead from the bottom of the service tank and terminate near the bottom of the settling tank. A non return valve should be installed in this line to prevent contaminating the service tank.

3.4.0 PURIFICATION OF HFO

The purification of HFO is the heart of the fuel treatment system. The use of disc-type centrifuges of the self cleaning type as purifiers have greatly facilitated the removal of water and solid contaminants in residual fuel. Prolonged and unattended operation of this machinery has

developed concurrently with the reliability, and effectiveness of the centrifuging process.

The efficiency of the centrifuging process depends on several factors, which are influenced from the operational or design aspect of the equipment. The operational factors include the position of the oil/water interface, the residence time of the fuel in the bowl, the temperature and thus the viscosity of the fuel, the rate of oil throughput and the density of the fuel. The design factors are the angular velocity of the bowl, the inner and outer radii of the discs, the number of discs, the spacing between discs and the cone angle of the discs (Clark 21/9).

Purifiers employ a water seal in the outer periphery of the bowl by the use of gravity disc. The gravity disc is selected based on the density of and the temperature at which the fuel is to be treated. The gravity disc determines the position of the oil/water interface in the bowl. Excess water is continuously expelled through the outer channel of the bowl via a centripetal pump.

The correct gravity disc size is essential for efficient separation of fuel and contaminants. The use of a larger gravity disc than required is readily visible to the operator by the presence of fuel in the water outlet. Unlike the latter, the use of an undersized gravity disc does not provide the operator with visible signals of a malfunctioning purifier. Therefore, the most accurate quotation of the density of the fuel is essential in determining the correct gravity disc size.

The relative viscosity of the fuel can be decreased by increasing the temperature of the fuel. The lower the viscosity, the less time is required for water and contaminants to travel through the fuel at any constant centrifugal force developed in the purifier. However, purifiers operate at atmospheric pressure, thus, the upper temperature of fuel to be treated is limited by the boiling point of water. To assure that the water seal in the bowl is not broken, fuel temperature is kept below 100°C, preferably 98°C.

With the stated restraints on fuel temperature, the operator is therefore left with one factor to improve the efficiency of the process. Increasing the time required for the fuel to transit the purifier's bowl is the other factor. The longer the residence time of the fuel in the bowl, the further outward contaminants would travel for a given constant viscosity and centrifugal force developed in the purifier's bowl.

To accomplish the foregoing, the rate of fuel throughput in the bowl is crucial. The lower the throughput, the longer is the residence time of the fuel in the bowl. Operators should employ purifiers with low throughput and use more than one unit when necessary to match consumption. An analysis of purifier efficiency versus throughput and interface position is shown on fig. 3.1.

The density, other than its relevance to the selection of the gravity disc, is a limiting factor in the separation process. The higher the relative density difference between two intermixed liquids, the easier it is to separate them mechanically. A fuel density of about 0.991

g/ml has been established as the upper limit for effective separation of fresh water from fuel in conventional purifiers. See fig. 3.2.

3.5.0 CLARIFICATION OF HFO

Clarification of HFO involves the removal of insoluble contaminants in the fuel based on the difference in relative density. Solid contaminants and water collect in the outer periphery of the bowl. Water accumulated in the outer periphery of the bowl would be carried out with the treated fuel between de-sludging.

Clarifiers are used extensively in the two stage fuel treatment process to remove contaminants left over from the purifiers. Clarifiers do not use a water seal and therefore need no gravity disc for positioning the oil/water interface. However, all the other factors associated with purification is relevant for efficient clarification.

3.6.0 TECHNOLOGICAL DEVELOPMENT IN CENTRIFUGING HFO

Large slow speed diesel engines have proven capable of burning fuels with density and viscosity well above 0.991 g/ml and 380 cSt at 50°C respectively. These cheap low quality fuels are available and attractive to ship operators as a means of reducing their operational cost. Fuel cost can amount to 50% or more of the total daily running cost of a vessel depending of the grade and price fluctuation of fuel.

The apparent restriction on the use of low grade HFO in the past decade was the density limitation of conventional centrifuging equipment. Manufacturers of this equipment have explored several possibilities and were successful in overcoming the density limitations with respect to current and future grades of HFO. The new generation of centrifuges and their features will be discussed with reference to the manufacturers.

3.6.1 ALFA-LAVAL ALCAP FUEL TREATMENT SYSTEM

Alfa-Laval developed the ALCAP fuel treatment system with its new generation of the FOPX separator. The advantages of the ALCAP system can best be summarized as follow:

1. The FOPX employs a one size flow-control disc, thereby eliminating the gravity disc and its associated problems;
2. Fuel with density up to 1.010 g/ml can be centrifuged with efficient separation of water, solids and sludge;
3. No water seal is necessary, and the combined purifier and clarifier functions can be achieved simultaneously in one machine;
4. The equipment and system was made simple, fully automatic and reliable.

To achieve this breakthrough, Alfa-Laval expanded on the fact that at 98°C, the relative density of fresh water is higher than fuel with density of 1.010 g/ml. See fig. 3.2.

A transducer is installed in the clean fuel outlet to measure the water content. The measured water content

value is transmitted to the MARST 1 microprocessor which opens a water drain valve in case of high water contamination. Normal centrifuging operation is uninterrupted during this period.

The normal Alfa-Laval partial de-sludging principle is maintained and the interval is usually set for 15 minutes. However, when water content in excess of 0.2% is measured, the MARST 1 sends a signal to the IPC/EPC program unit to activate an intermittent sludge/water discharge without interrupting the centrifuging process. See fig. 3.3 for ALCAP layout and table III-1 for onboard test results of the ALCAP system.

3.6.2 WESTFALIA NEW GENERATION SEPARATORS

Westfalia has developed three lines of separators capable of treating fuel with densities up to 1.010 g/ml. The separators are called the Verizone, Secutrol and Unitrol respectively.

The Verizone separator is used as a purifier. The principle involved is an automatically adjusted separating zone. One size gravity disc is used to treat fuel with densities from 0.960 to 0.995 g/ml. The interface is moved within a predetermined zone depending on the density, viscosity, temperature and throughput of the fuel to be treated. Certainly, this development eliminates problems associated with gravity disc selection.

The Secutrol separator clarifier incorporates a self thinker de-sludging control system. This system controls sludge discharge based on a timed sequence as well as the amount/position of contaminants in the bowl's sludge chamber.

The Secutrol clarifier control system in conjunction with the time dependent sludge discharge program, utilizes liquid pressure on a pressure switch (PSL) to determine the amount/position of sludge in the bowl. When sludge accumulates in the sludge chamber, the liquid passage is restricted thus resulting in a corresponding pressure drop measured by the pressure switch. The pressure switch transmits a signal to the VESA E-2 program unit which than activates the sludge discharge system. See fig. 3.4 for Verizone-Secutrol layout.

The Secutrol clarifier is used in series with the Verizone purifier in the two-stage fuel treatment plant. The Secutrol sludge control mechanism controls the sludge discharge intervals for both equipment.

The Unitrol clarifier/purifier developed by Westfalia is a versatile separator which expands on the Secutrol clarifier principle. A conductivity sensor is used to monitor the water content rather than a pressure switch. The presence of a predetermined quantity of water would open a water discharge valve and close the recirculating valve. When the water content is lower than the preset value, these valves operations are reversed. Normal timed sludge discharge is also incorporated. See fig. 3.5 for the Unitrol layout.

A combination of the Unitrol and Secutrol separators as a fuel treatment plant gives it the capability of handling fuel up to 1.010 g/ml. Neither separator uses gravity discs. When operated in series, the two-stage fuel treatment is self-adjusting from purifier/clarifier to clarifier/clarifier depending on the nature of the contaminants in the fuel. Fuels with varying densities can be treated without manually adjusting the equipment.

3.7.0 OPTIMUM CENTRIFUGE APPLICATION

Purifiers are extremely useful in the removal of liquid contaminants from fuel. Shipboard fuels are more likely to be contaminated by salt water, and in some rare cases, highly corrosive mineral acids such as sulphuric and hydrofluoric acids from the refinery. Irrespective of fuel analysis results, no HFO should be allowed to enter the engine without purification.

The best purifier adjustment when a relatively large water content is detected should be as follow:

1. Operate two purifiers in parallel at reduced throughput commensurate with consumption;
2. Never operate purifiers in series. The second purifier will remove an insignificant quantity of contaminants compared to the first purifier.
3. Maintain a constant fuel inlet temperature to avoid interface disposition.

When solid contaminants are extensive, the fuel treatment plant should be operated in series (purifier/clarifier arrangement). The de-sludging period should be optimized

taking into consideration the amount of contaminants and the sludge discharge mechanism. See fig. 3.6.

Bowls with total de-sludging systems will lose up to five times more fuel than an equivalent partial de-sludging bowl during sludge discharge. The latter comparison sometimes eludes operators when taking stock of fuel. However, to maintain the effectiveness of the centrifuging process, a compromise must be reached between fuel loss and clean fuel.

3.8.0 THE ROLE OF EMULSIFIERS OR HOMOGENISERS

The terms emulsifiers and homogenisers are synonymous in their application. The use of this equipment affects several aspects of fuel treatment and combustion. This equipment, when used properly, can reduce detrimental pollutants found in exhaust gas.

Homogenisers as fuel treatment equipment would improve fuel quality prior to combustion. CIMAC accounts for the positive effects as follows: "[To emulsify] the water which may be present in the fuel. This is useful if, after treatment, small slugs or large droplets of water are still present, which can cause irregular combustion. Water emulsified to droplets smaller than 5 microns will generally do no harm to the combustion process and can even improve it...
[To reduce] agglomerates of asphaltenes in size and [to] thoroughly [disperse] them throughout the fuel. This is useful in cases where asphaltene coagulation occurs, which can happen with unstable fuels or by blending incompatible fuels. Homogenising will create a fuel of uniform

structure and consistency and thus helps to prevent deposits in fuel injection equipment or clogging of filters" (CIMAC 19).

3.8.1 HOMOGENISERS AND FUEL TREATMENT

Homogenisers are not recommended to be used as a replacement for centrifuging plants. Homogenisers will not remove destructive contaminants such as catalyst fines. Salt water and acids found in the fuel would remain in the emulsified fuel. Their detrimental effect on engine components would not be reduced.

Homogenisers should not be installed before the centrifuging plant. In as much as this would reduce the amount of separated sludge, the centrifuge would be ineffective in removing emulsified liquids and to a lesser extent, contaminants below 5 micron. Homogenisers when used before a safety filter prior to the engine would reduce filter clogging. Small filter mesh in the order of 10-5 microns can be installed to effectively trap residual solid contaminants.

3.8.2 HOMOGENISER AND THE COMBUSTION PROCESS

Homogenisers have been used to improve the combustion of HFO in diesel engines. To achieve improved combustion, fresh water in relative proportion to the fuel is passed through the homogeniser (emulsifier) thereby producing emulsified fuel. Emulsified fuel with 30% water has been burnt successfully in diesel engines, while a Japanese research has claimed success with up to 80% water.

Results from the burning of emulsified fuel have shown that the water droplets create microexplosion which leads to secondary atomization of the fuel. This phenomena leads to improve fuel vapor generation and a subsequent increase in burning rate (P.S. Katsoulakos 3).

However, there are mixed results with regards to the efficient upper limit for water content. A 10% water content for engine load above 50% seems to produce the best combustion results. The outcome of the foregoing process is a 1-5% reduction in specific fuel consumption for older generation engines.

Further evaluation of emulsified fuels has shown that water droplets promote the formation of hydroxl radicals (OH) which reacts with the hydrogen atoms in the hydrocarbon molecules. This reaction, amongst other things, results in lower combustion temperatures and a subsequent reduction of environmentally harmful nitrogen oxides.

Newer and more efficient diesel engines thrive on the principal of higher injection pressures and faster burning rates as inherent components of fuel efficiency. It is argued that the process which occurs due to the latter consideration is similar to that accomplished by the water droplets. Therefore, emulsified fuel might not provide additional improvement in these engines. However, the possibility of reducing pollutants, coupled with the prospect of cleaner engine and exhaust gas user equipment are factors to be considered when employing homogenisers.

3.9.0 FILTRATION

The use of filters is a necessary element in the fuel treatment plant. Filters are used in varying sizes in the transfer, treatment and pre-injection systems.

Filters fitted in the pre-injection system (between service tank and engine) are core elements of the fuel system. Main filters used in this section are normally of the 25 micron nominal mesh size. Smaller mesh sizes of 5 microns are being installed as safety filters close to the engine. These filters also provide indication of the effectiveness of the centrifuging process.

Safety filters are prone to clogging due to coagulation of asphaltenes (thermal instability). To alleviate this tendency, ultrasonic waves are introduced on the filter surface thus breaking down the organic particles in similar fashion as would mechanical homogenisers (CIMAC 21).

The extent to which safety filters are used will depend on the equipment cost and the resolve of the operators to appreciate their effects. Main filters of the size mentioned earlier are certainly *not* an optional item. This filter must be design to withstand high temperatures as well as incorporate a flexible duplex design, preferably of the self-cleaning type. See fig. 3.7 for a suggested full fuel plant layout.

3.10.0 FUEL ADDITIVES

Fuel additives remain a controversial facet in the treatment of HFO. The professed achievements in retarding the adverse effects of the undesirable components of HFO and the economical aspects for the use of additives have not been unequivocally established.

Additives are usually concentrates of powdered chemicals in oil. To fully achieve effective results from the use of additives, homogenisers should be employed to assure that the additives are well dispersed in the mixture.

Additives are available for dealing with the detrimental effects of microbiological growths, sulphur, vanadium, nickel, sodium and sludge formation. Improvements in engine and equipment design, in particular, combustion chamber accessories and fuel treatment plants, coupled with better operational parameters awareness, improved lubricating oil quality and application methods have all provided proven remedies as compared to costly additives.

ANNEX—B

Purifier separation efficiency of catalyst fines v. flow rate and interface position

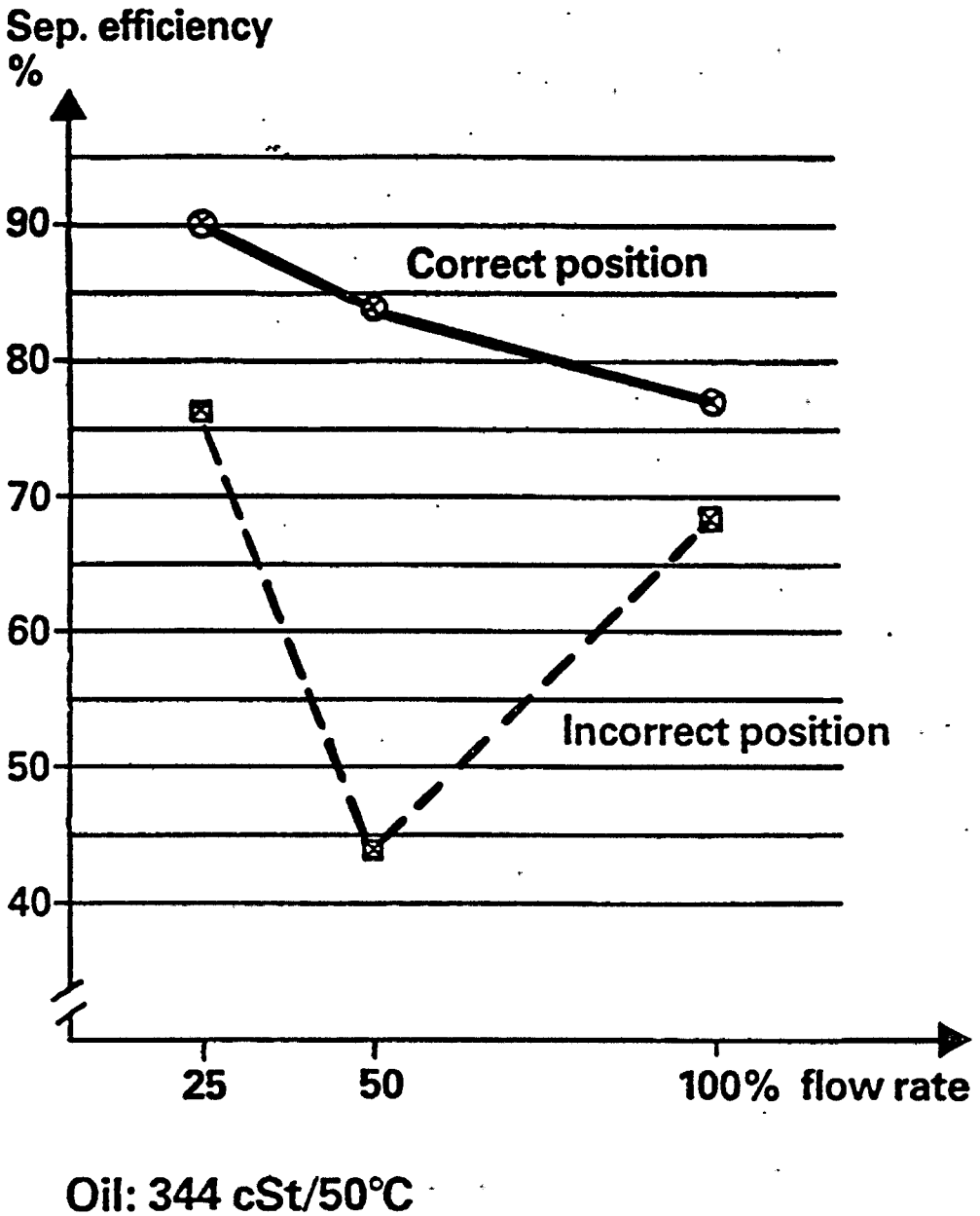


Fig. 3.1 The effect of incorrect interface position and varying flow rate on the removal of catalytic fines in centrifuges (Alfa-Laval).
Source: Det Norske Veritas

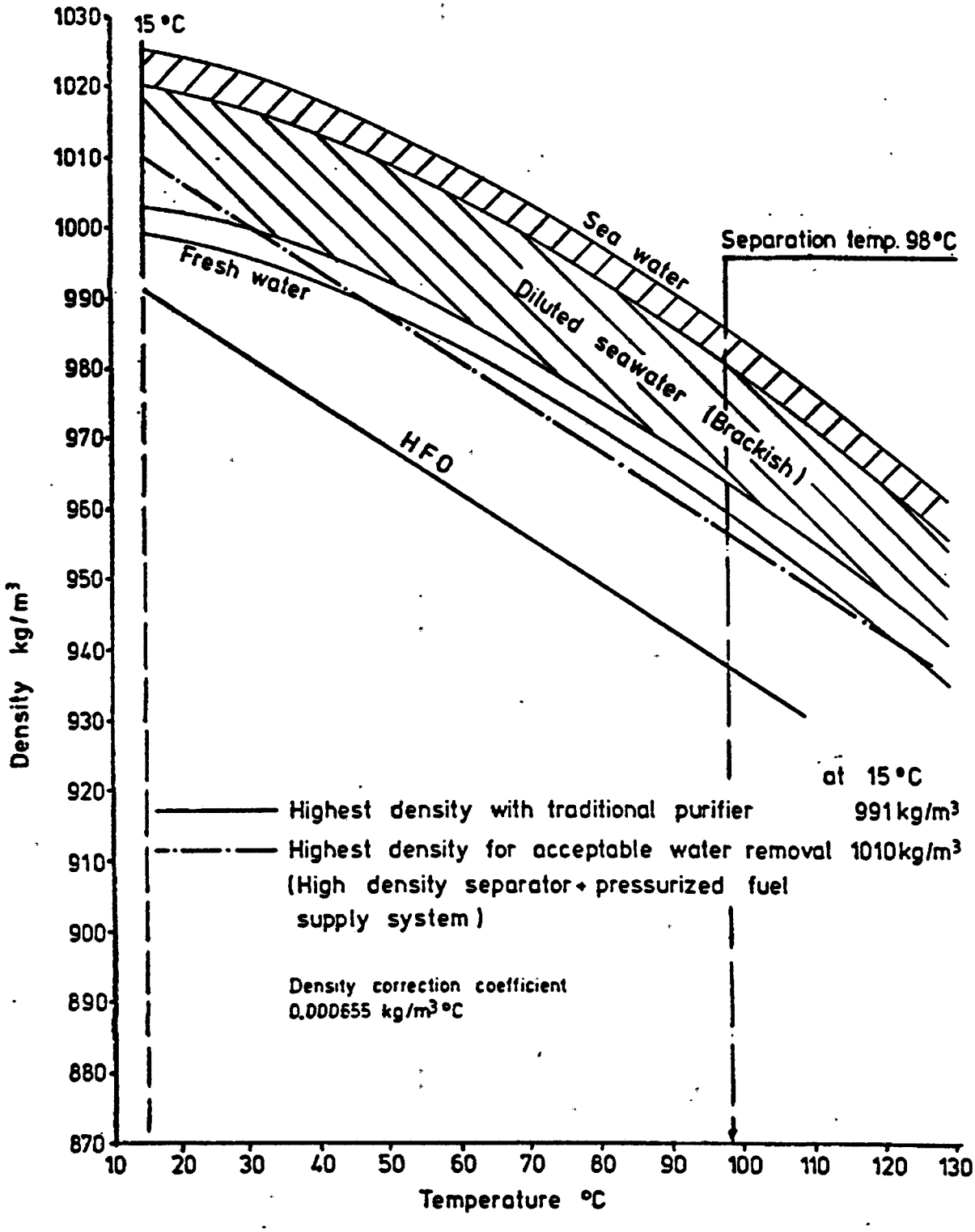


Fig. 3.2 Density Variations with respect to temperature of HFO and Water (Courtesy of Sulzer).

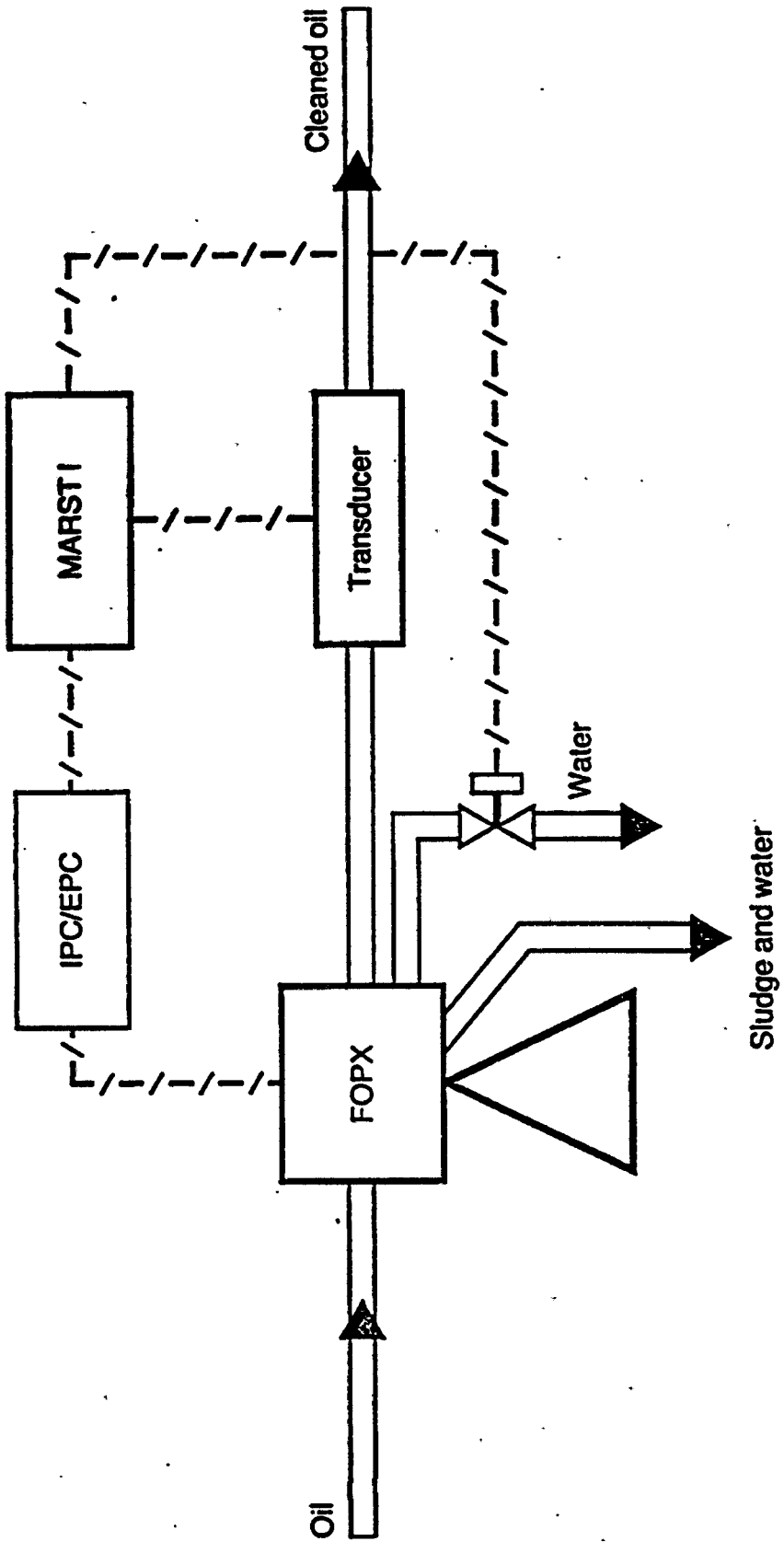


Fig. 3.3 ALFA-LAVAL ALCAP System Layout (Courtesy of ALFA-LAVAL Ltd.).

Water dosage before separator	H_2O (%mass)		Na (ppm)		Al (ppm)		Si (ppm)	
	Before	After	Before	After	Before	After	Before	After
Fresh water (evaporators) Density 1.000 at 19°C*	3.0	1.2	34	30	18	4	33	10
	1.8	0.8	—	—	—	—	—	—
Contaminated fresh water (brackish. Rotterdam) Density 1.001 at 28.5°C	2.4	0.6	88	42	16	3	27	7
Sea water† (North Sea) Density 1.026 at 15°C	13.0	1.2	1550	97	14	3	27	8
	1.3	0.5	110	71	18	3	33	10
	0.45	0.2	58	35	18	3	33	10

*Measured on board ship.
†ASTM D1298.

Table III-1 ALCAP Separator trials on fuel density of 1.013. (Courtesy of Sulzer).

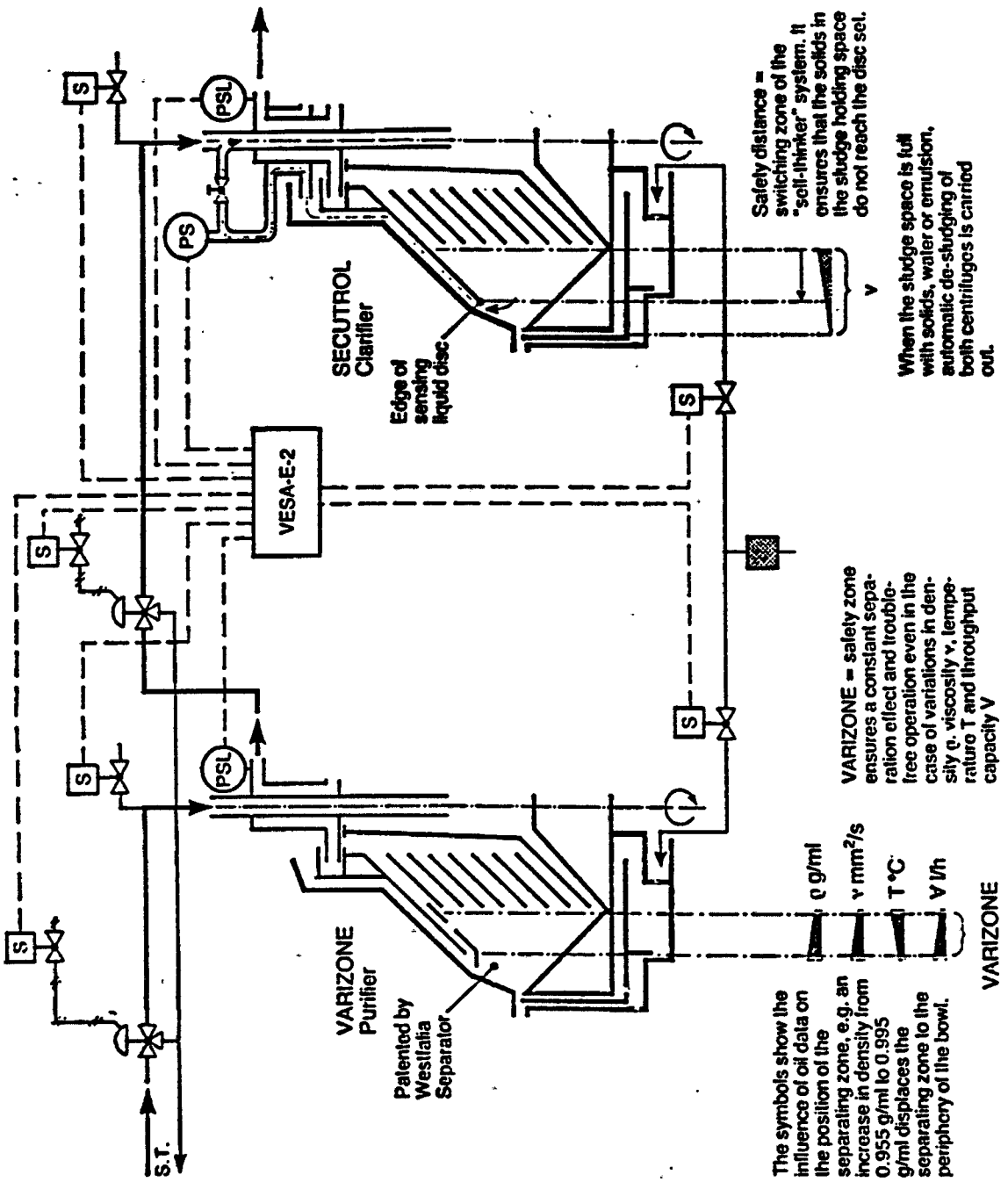


Fig. 3.4 Westfalia Varizone and Secutrol Fuel Safety Treatment Plant Layout.
(Courtesy of Westfalia Separator AG.)

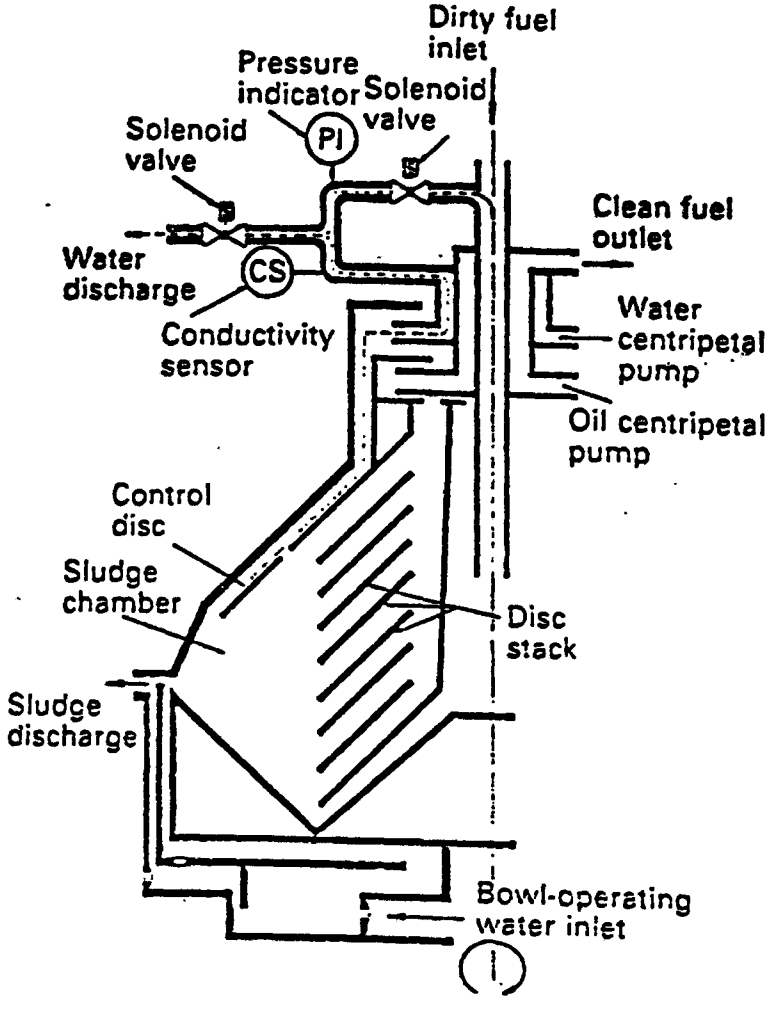


Fig. 3.5 Unitrol Separator
(Courtesy of Westfalia Separator AG.).

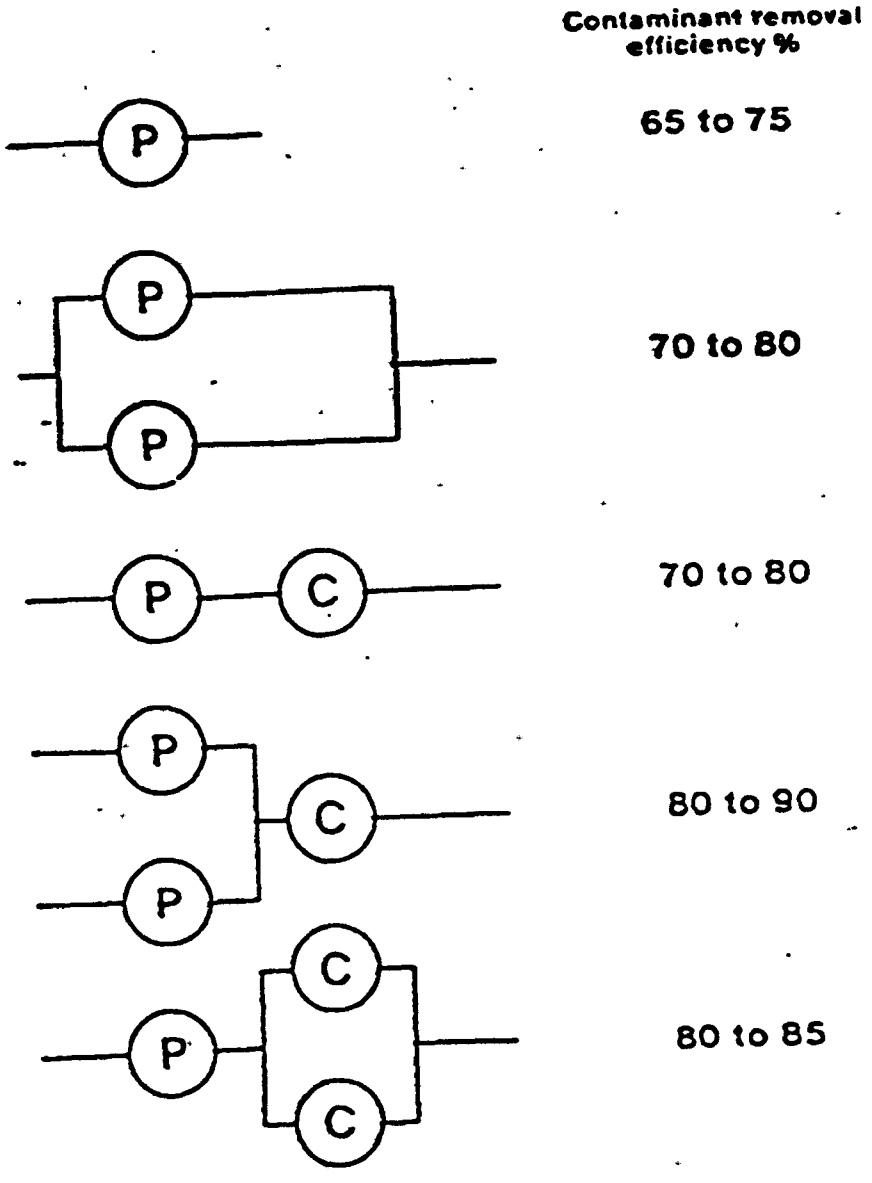


Fig. 3.6 Optimum conventional centrifuge configuration efficiency.

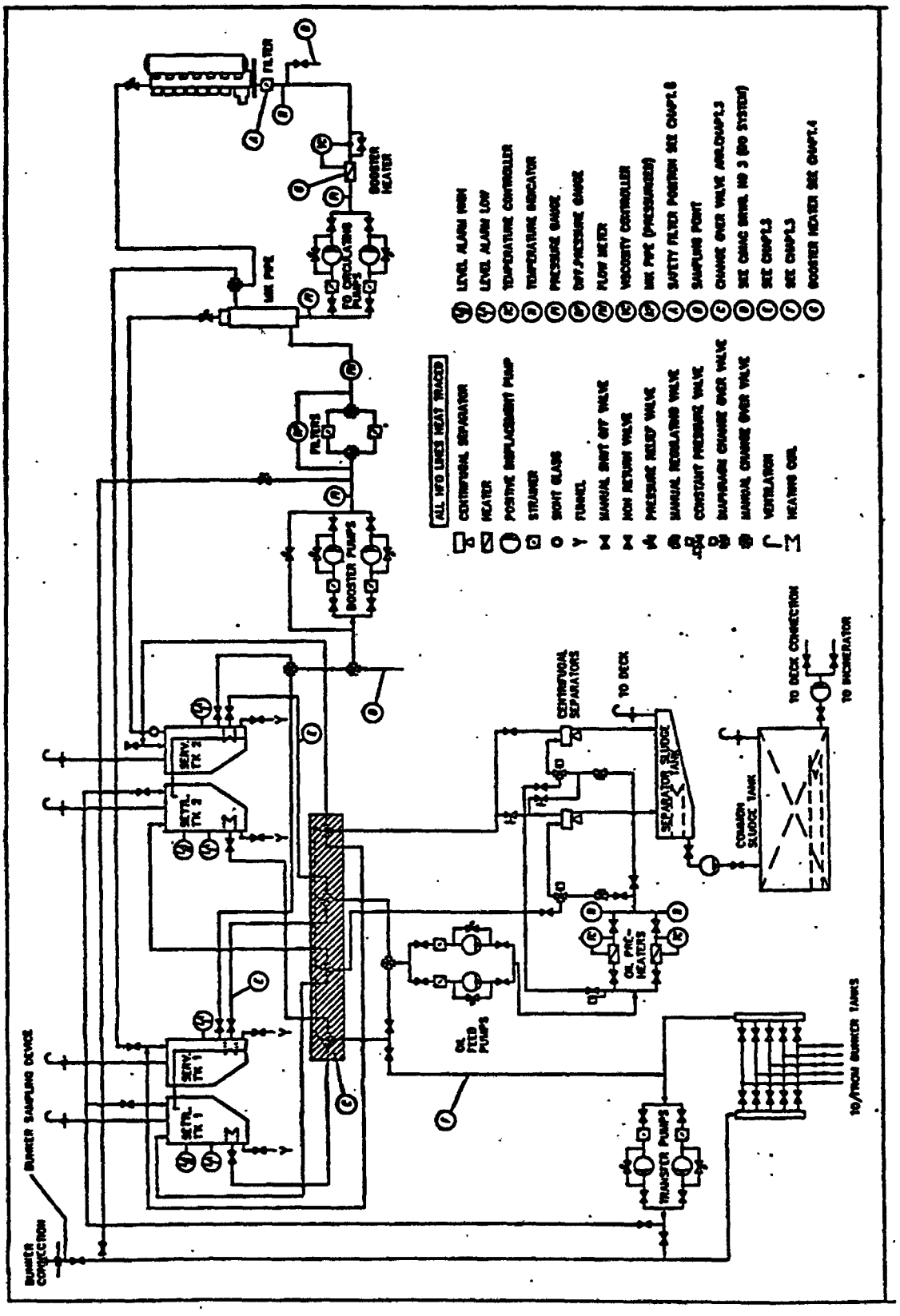


Fig. 3.7 A Full HFO fuel plant layout
(Courtesy of CIMAC).

CHAPTER IV

FUEL BOOSTER SYSTEM AND INJECTION EQUIPMENT

4.1.0 INTRODUCTION

The booster and injection systems provide the final conditioning of fuel prior to the combustion process. Some components of these systems are subject to the detrimental effects of contaminants found in fuels. Other components provide the final separation mechanism of contaminants from the fuel.

This chapter will examine the various aspects of these systems as they relate to the final conditioning of the fuel. The operational implications of fuel quality with respect to these systems, as well as the maintenance and monitoring realms will be discussed.

The technological developments relative to these systems vis a vis the newer generation engines capabilities to burn poor quality fuels will be explored. The inherent design features and their effects on the efficiency of the combustion process will be cited.

It is without doubt that the human element involved in the effective operation of these systems is crucial. The process of man-machine interface, particularly the necessary background for making decisions related to these systems, will be emphasized.

4.2.0 FUEL BOOSTER SYSTEM

The conventional booster system (CBS) incorporates the service tank as a reservoir. Other components of this system are the main filter, flowmeter, fuel booster pumps, fuel heaters, viscosimeter, hot filter, associated piping to injection pump and return piping to a mixing tank. A homogeniser may be installed as an optional equipment depending on the operator's preference.

4.2.1 SERVICE TANK

The design and operational aspects of the service tank with regards to the fuel treatment plant was discussed in the previous chapter. However, the service tank is the link between the treatment and booster systems. Therefore, its role in the booster system is henceforth considered.

Contaminants that are not removed from the fuel by the centrifuges will accumulate in the service tank over a period of time. When sloshing occurs, these contaminants are dislodged from the bottom of the tank and are than carried over into the booster system. A double service tank system would give the operator the flexibility to periodically drain and clean a service tank without interrupting the engine operation.

The service tank provides a positive suction head to the booster pump. The outlet from the service tank should be above the bottom of the tank. The vertical distance from the service tank outlet to the booster pump should be sufficient to overcome the pressure drop in the suction filter and flowmeter.

The location of the service tank outlet also determines the location of the outlet from the mixing tank. DNV suggests that "the vertical distance from the outlet of the service tank to the outlet of the mixing tube should be at least 2 meters. If the distance is too small, the result may be that the booster pumps empty the mixing pipe faster than fuel enters it. Air will then be drawn in through the venting pipe to the mixing pipe and the result will be pump cavitation and loss of power to the engine" (Veritas 72).

4.2.2 THE MIXING TANK

The mixing tank is usually a cylindrical tank installed at the level of the service tank. The mixing tank is sometimes referred to as the standpipe, mixing tube or mixing pipe. This tank is installed primarily on vessels which operate normally on HFO and then marine diesel oil (MDO) for maneuvering and periodic shutdown.

The excess high temperature fuel (110-145°C) from the injection system is returned to the mixing tank. This hot fuel re-enters the booster system after the flowmeter. The high temperature fuel entering the mixing tank is likely to boil off and foam. This could cause oil and vapor to come out from the venting pipe (Veritas 72).

To reduce the operational difficulties encountered by engineers, there are some design and operational considerations which need to be discussed. The outlet of the mixing tank should be at least two meters below that of the service tank. The height of the mixing tank should extend not less than half meter above the highest fuel

level in the service tank. These two design aspects will compensate for the difference in relative densities of the fuel in the service and mixing tanks. Problems associated with flow irregularity and cavitation in the booster pump would also be minimized in the conventional booster system.

The location of where the returning fuel is released into the mixing tank is very important. This location should not be too near the fuel outlet from the mixing tank. This design consideration would prevent vapor contained in the hot returning fuel from entering the system. Secondly, the location should not be above the fuel level in the mixing tank. This would prevent foaming in the mixing tank. The returning fuel should be released into the fuel in the mixing tank. It is recommended to release the fuel into the mixing tank at a level slightly below the height of the low level alarm in the service tank (Veritas 72).

The mixing tank is the largest volume in the booster system where fresh fuel or different grades of fuel can mix. Normally, the fuel circulating in the system is about three times the amount consumed by the engine at full load. When changing over from HFO to MDO, the operator needs to acknowledge the latter and proceed cautiously. The operator should insure that no undue dynamic stress on the injection equipment occurs, particularly when the fuel temperature decreases prior to the arrival of MDO at the injection pump. To switch from MDO to HFO requires gradual heating of the fuel to about 85°C in order to prevent seizure or rupture of the injection equipment.

It should be realized that the fuel level in the mixing tank is determined by the fuel level of the service tank with considerations for the relative fuel densities. Based on the latter, the MDO service tank level should be as close as possible to that of the HFO service tank prior to switching over. On the contrary, a relatively higher level in the MDO service tank will cause pronounced viscosity/temperature fluctuations during the critical period immediately following the change over to HFO. The above mentioned scenarios should be avoided.

A very low level in the MDO service tank relative to the level in the HFO service tank will promote MDO stagnation in the mixing tank, as well as a sudden rise in the mixing tank level when the engine has been switched over to HFO. This could cause fuel to be expelled from the ventpipe. In designs where the ventpipe from the mixing tank is relatively small, and the overflow piping from the mixing tank is connected to one of the fuel tanks, a prolonged siphon effect could be created.

4.2.3 THE BOOSTER PUMP

The booster pump should be capable of supplying fuel to the injection system at pressures up to 10 bars. There must be two pumps with one in service and the other as a standby. These pumps are normally fitted with internal relief valves. These valves serve as safeguards against exceeding the highest acceptable pressure in the booster system.

These pumps must be capable of handling fuel at high temperatures. The fuel supply to these pumps should have

a positive suction head. The pressure delivered by the booster pump should be about 1 bar above the boiling point of water at the highest fuel temperature encountered in the system. The delivered pressure is regulated by a pressure sustaining valve located between the mixing tank and the common fuel supply line to the injection pumps.

Normally, these pumps do not pose any operational problems. However, a careful and regular examination of the pump glands for leakage should be practised. An experienced operator with the appropriate knowledge of the pump's condition, can deduce from observing the frequency and quantity of gland leakage, that abrasive contaminants may be present in the treated fuel.

4.2.4 FUEL HEATERS

Fuel heaters are essential elements of the booster system. Two heaters in parallel are normally installed with one of them as a standby. Each heater should be capable of raising the fuel temperature from 60 to 170°C at full engine load. The temperature at which the fuel is to be heated is determined from a viscosity temperature chart. However, a viscosimeter can automatically regulate the fuel viscosity/temperature relative to the determined injection viscosity.

Some older ships were designed to operate on IFO 180/ISO RME-25. Consequently, their heaters were designed to meet the temperature/viscosity requirements for this grade of fuel. With main engines being capable of burning lower quality fuels, mainly IFO 380/ISO RMH-35 and above, the reserve heating capacity of these heaters became inadequate.

Operators were confronted with the problem of maintaining the right viscosity, even with clean heaters. As a compromise, both heaters were used simultaneously. The obvious consequences of this practice was more frequent and increased fouling of these heaters. This can be attributed to the low flow rate through both heaters when they are operated in parallel. Furthermore, it became very difficult to remove one of the heaters from service for cleaning without interrupting the operation of the engine.

To address all of the foregoing operational difficulties encountered on older ships, an additional large heater capable of meeting the heating requirements should be installed. The original two heaters can than be used as a standby unit.

The quality of HFO has a direct bearing on the effectiveness of these heaters. Other than meeting injection viscosity requirements of poor quality fuels, the carbon residue content and stability are also factors to be considered when operating heaters.

A high carbon residue content could accelerate the formation of carbonaceous deposits on heating surfaces. This is particularly true where the heater is overloaded and relatively cold fuel enters the heater. These conditions would lead to overheating of the oil film in contact with the heater surface, thereby resulting in carbonaceous fouling. Irregular flow through the heater would also contribute to fouling.

The original stability of the fuel also dictates its thermal stability. The unwanted prospect of thermal instability is prevalent from the perspective of the service and mixing tanks where stratification and asphaltene sedimentation could occur. The consequence of thermal instability is irregular heat supply to the heater in order to maintain a constant viscosity of the stratified fuel. A reduction in fuel flow through the heater would then cause solids and sludge to fall out of the fluid stream. This would increase solidified deposit formation on heating surfaces as well.

4.2.5 VISCOSIMETER

The viscosimeter is a necessary component of the booster system. The major parameter required by the injection system from the booster system is the right viscosity. The definite correlation of viscosity and temperature although true for a given fuel parameter, does not hold true for HFO and certainly blended HFO. This is due primarily to fuel stability which is a relative parameter, and thermal stability which is often unavoidable. Therefore, temperature as a criterion for controlling viscosity is not a suggested practice. A viscosimeter will measure the actual viscosity and subsequently adjust the heat supply/temperature to maintain the required viscosity.

The operator should countercheck the viscosimeter's performance with the temperature of the fuel as a guide. The operator must first realize that the recommended viscosity for the injection system should be directly quoted with reference to the location in the system.

Viscosity increases with pressure. Thus, the viscosity at the injector could be 5-10 cSt higher than the supplied viscosity at the injection pump. The operator should make use of the viscosity-temperature-pressure relationship curves to determine the right injection viscosity and adjust the viscosimeter accordingly. See fig. 4.1.

4.2.6 FILTERS AND FLOWMETERS

Fuel filters, as discussed in chapter III-3.9, covered filters in the booster system. A coarse filter installed before the fuel flowmeter provides protection for this sensitive instrument. Contaminants trapped in the filter provide a clear indication of the fuel cleaning process and the condition of the service tank.

Hot filters or safety filters should be installed after fuel heaters as recommended. These filters' mesh sizes depend on the fuel treatment system installed. However, both filters should be periodically inspected to insure that filtering elements are in good condition irrespective of the indicated operational condition of these filters.

Flowmeters vary with type, complexity and technology. The conventional rotary vane and oval-wheel flowmeters provide a substantial resistance to flow, with the latter providing the larger resistance. Their rated capacities are often four times the flow capacity of the fuel system. These two mentioned flowmeters are much cheaper and more accurate than the acoustic flow sensor type which practically offers no resistance to flow.

The operator is continuously pressed to give accurate account of the fuel consumed. Therefore, the operator must be aware of the correction factors of these meters. In the case where electronic measuring and computerized monitoring systems are employed, the degree of accuracy must be initially established and then verified periodically.

See fig. 4.2 for a suggested conventional fuel booster system layout.

4.3.0 PRESSURIZED BOOSTER SYSTEM (PBS)

The pressurized booster system (PBS) is a recent development towards improving the plant's overall capability to burn poor quality fuels. The primary feature of this system involves a higher than atmospheric pressure in the buffer tank or venting unit. This reduces the amount of volatile fuel components and water which would evaporate at atmospheric pressure relative to the high temperature of the returned fuel.

The system incorporates a low pressure booster/supply pump between the service tank and buffer tank. This booster pump supplies fuel to the buffer tank at a higher pressure than the corresponding boiling point of water at the returned fuel temperature. A de-aeration valve installed in the ventpipe of the buffer tank maintains the pressure on the buffer tank and the fuel return line.

A high pressure booster/circulating pump is installed after the buffer tank to supply the injection system. The delivered pressure of this pump could range from 4-15 bars depending on the injection system design. A pressure

sustaining valve located in the fuel distribution system and downstream from the injection pumps maintains the required back pressure.

There are two PBS being used by Sulzer and MAN-B&W respectively. Common to both systems are two inherent safety features. Firstly, both systems incorporate pressure regulating valves or overflow valves between the delivery and suction sides of the supply pump. This feature would prevent the build up of excess pressure in the buffer tank.

The second safety feature takes account of a possible de-aeration valve failure. If such failure occurs, the PBS would operate as a conventional booster system with boil off tendencies. One system vents the buffer tank to the service tank and the other provides a line after the de-aeration valve to a fuel tank. See fig. 4.3 for a Sulzer PBS and fig. 4.4 for a B&W PBS layout.

A comparison of the PBS with the conventional booster system reveals that problems associated with mixing tanks in conventional systems are minimized or eliminated by the PBS. Another positive aspect of the PBS is that the buffer tank size and height can be reduced. Restrictions on the tank's precise location are also eliminated.

As fuel quality/viscosity decreases, the corresponding higher temperature required for injection viscosity can be achieved without the threat of massive boil off. An example of the latter is at 4 bars, water boils at 144°C. Therefore, a mixing tank pressure above 4 bars would keep water and volatile components as liquid throughout the system.

There are two concepts which could change the current PBS equipment layout. The high pressure booster pump and the pressure sustaining valve could be eliminated. Subsequently, the low pressure booster pump would than supply the entire system at the required pre-injection pressure. The second concept involves replacing the high pressure booster pump with a comparable homogeniser unit.

4.4.0 FUEL INJECTION PUMP

The fuel injection pump along with the injector are the most delicate components of the fuel system. Besides the injection pumps known functions of accurately metering the fuel delivered to the injector/cylinder and delivering the fuel at the right time and pressure, it must also endure stresses caused by load fluctuations and changes in the fuel viscosity and temperature.

Compounding the foregoing demands on the injection pump is the introduction of variable injection timing (VIT). The latter consideration will be dealt with separately. However, VIT introduced additional movements in the injection pump, particularly the helix-type pump and to a lesser extent the valve-controlled pump. This added feature may in itself reduce the mean time between overhaul of the injection pump, thereby leaving no room for the use of contaminated fuels. See fig. 4.5 for Sulzer and MAN-B&W fuel pumps respectively.

The plunger and barrel of the injection pump are accurately machined to a surface finish of less than 1 micron and a clearance of 7-10 microns. Any abrasive particle or catalyst fine not removed by the treatment

plant could be catastrophic for these components. Scratched unusable fuel pump plungers and barrels are not uncommon. This can be attributed to heavily contaminated fuel and the operators inability or negligence to interpret fuel quality tests results. The latter situation often results in improper adjustment of centrifuge equipment. In systems where safety filters are fitted, more often than not, they are perforated and remain unnoticed by operators.

The above scenario should not create doubts about the technical capability or the resolve of the shipboard operator. It illustrates the lack of concise and understandable reference brochures on fuels being made available to the shipboard operator.

Other than solid contaminants which pose the greatest threat to fuel pumps, there have been isolated reports of unusual fuel pumps plungers and valves seizures. The fuel pump plungers and valves were found covered with blue-blackish lacquer. Detailed investigations revealed the presence of inorganic acid, precisely fluoride in the form of hydrofluoritic acid. This type of inorganic acid and sulphuric acid are used in "alcylation processes" in refineries. Although it was suggested that these acids may enter the fuel stream by accident, it is worth noting this possibility and the associated effects.

4.5.0 VARIABLE INJECTION TIMING (VIT)

VIT is the delicate fuel injection timing control mechanism installed on the new generation of diesel engines. The concept of the system is to maintain the design maximum combustion pressure at varying engine loads

above 85%. With all engine parameters constant and combustion chamber members in ideal condition, a drop in maximum firing pressures across all cylinders due to poor quality fuels can be automatically or manually adjusted by VIT.

More importantly, the VIT system makes the intricate time of fuel injection load dependent. This feature prevents fluctuations of maximum combustion pressures from the ideal. Fuel savings of about 2 g/bhph can be achieved with this system.

A comparison of combustion pressures over varying loads with and without VIT, as well as the difference in combustion pressures due to ignition quality versus engine output can be seen on fig. 4.6. The noticeable difference in combustion pressures as a result of lower fuel ignition quality can be significantly reduced, if not eliminated by the VIT fuel quality setting mechanism. A comparison of fuel injection timing with and without VIT is shown on fig. 4.7 with a clear indication of the shift in the beginning and the end of injection at different loads.

The Sulzer concept of the VIT incorporates a fuel quality setting mechanism. Once the fuel (ignition) quality is known, and engine combustion parameters measured, the timing of injection can be manually advanced or retarded. The latter provides a more manageable range for the automatically controlled load dependent element. The Sulzer VIT system controls the closing of the suction valve to begin fuel delivery and the opening of the spill valve to end fuel delivery. See fig. 4.8.

The MAN B&W VIT system incorporates a mechanism to lift or lower the fuel pump barrel relative to the cam. This action changes the effective stroke in response to a change in engine mean pressure at the desired load. A second linkage rotates the plunger thus varying the time of injection. See fig. 4.9.

4.6.0 FUEL INJECTORS

The fuel injectors are exposed to varying degrees of temperatures. The higher temperature required to obtain the necessary fuel injection viscosity, and the high heat release in the cylinder, are contributory factors to the short time between overhaul and the duration of the injector nozzles.

In older generation engines with long fuel injector tips, severe abrasive wear of the injector orifices have been experienced. This phenomena becomes more pronounced when abrasive contaminants are present in the fuel.

High nozzle tip temperatures promote cracking of high asphaltene fuels. The separated heavier fuel components will form coke deposits around the nozzle orifices. These deposits known as "trumpets" could obstruct these orifices and cause fuel impingement on the cylinder liner and piston crown. This has resulted in cracked cylinder liners and piston crowns.

In newer designs of injectors, the exposed tip area has been significantly reduced. Although this development is significant, it does not eradicate the problem completely. In addition, the cooling of injectors has also assisted in

reducing tip temperatures, but not without drawbacks if improperly operated. If the injectors are cooled below the dew point of sulphuric acid during engine operation, especially at the end of the exhaust stroke, tip corrosion can begin. This is more pronounced where a high sulphur content fuel is used.

Some fuel injectors have been designed to facilitate fuel circulation through the injectors when the engine has been stopped. This concept greatly improves the berth to berth operation on HFO. It also reduces the tendency of blowback associated with non circulating injectors during engine startup. Heavy aromatic residual fuels are known to form sticky lacquer at high temperatures. This phenomena is enhanced if the fuel stability is questionable. Injector needles could be trapped open by this lacquer, thereby inviting blowback and carbon formation in the injector sac. See fig. 4.10 for Sulzer and MAN B&W improved HFO injectors.

Mitsubishi has developed a variable pressure-control injector. The concept is unique as it maintains a reasonably higher pressure than normal on the injector between 30 - 75% load.

Fuel injectors open at moderately preset pressures. However, the proper atomization of the fuel depends on the dynamic pressure of the fuel once the injector needle has been lifted. The dynamic pressure is developed by the fuel pump as a function of plunger speed (engine rev.) with all other parameters being constant.

As HFO ignition quality decreases, coupled with high asphaltene content, the extent to which fuel penetrates the combustion chamber and the size of the fuel droplets becomes critical. With the pressure-control injector, poor quality fuel can be properly atomized over varying engine loads. This system decreases deposit formation at low loads and improves the combustion efficiency. See fig. 4.11 for Mitsubishi pressure-control fuel valve operation diagram.

Injectors are also subjected to extremely high pressures of up to 1400 bars. Categorically, metallurgy has advanced to compensate for the dynamic loading imposed on injectors. The increased use of heat-resistant alloy steel and in some cases stainless steel, has increased the durability of the injectors. However, abrasive damage to injectors needles and guides, as well as high pressure erosion of needles and seats could be exaggerated if solid contaminants are present in the fuel.

4.7.0 MAINTENANCE AND OPERATIONAL ASPECTS

Proper maintenance of fuel booster and injection systems is essential to maintaining the plant's capability to burn HFO. Accurate records should be kept of each component's condition and maintenance requirements. These two interdependent fuel systems should not rely solely on planned maintenance (running hours). A systematic condition monitoring program should be executed to supplement the latter.

The maintenance requirements for the booster system should involve careful interpretations of fuel quality tests

results. Revealed quantities and types of contaminants should be related to a time frame for inspection of the service tank. This inspection should proceed irrespective of the type of centrifuge, or the performance of the down stream filters from the service tank. Filters should not just be cleaned. The trapped contaminants should be examined and identified when possible.

Maintenance of the booster pump is not particularly different from the normal requirement for pumps of this nature. Gland leakages should be routinely monitored. Persistent leakage over a short period could signal a significant concentration of very fine solid contaminants.

The heaters would require periodic cleaning from a temperature monitoring perspective, or better yet, the duration of service, which ever of the two is earlier. The mixing tank vapor trap or de-aeration valve should be cleaned periodically to ensure proper operation.

The fuel injection pumps should be monitored routinely for leakages. The control linkages to the fuel pumps should be checked periodically for loose components. Fuel pumps timing should be confirmed when feasible. When a pump is overhauled for routine maintenance, or due to leakage, the plunger and barrel should be examined for scoring marks. Scratched barrel or plunger surfaces should be replaced as a unit. Visible longitudinal grooves from end to end would promote leakage and possible seizure, as would non-continuous scoring marks.

The latter considerations apply equally for fuel injectors needles and guides. A good practice would be to have ample replacement nozzles on board. The delicate task of

reconditioning/rectifying nozzles on board by the use of grinding paste is completely unacceptable, especially for todays high power per cylinder engines. The same applies equally for older generation engines if the burning of HFO is to be efficient.

The maintenance of fuel injectors on board should consist primarily of cleaning the parts, examining them for corrosion and erosion, as well as the measurement and visual inspection of the orifices for size and out-of-round. The needle and guide should be inspected for scoring marks. Metal to metal sealing surfaces other than the needle and seat should be properly maintained.

The cleaned injector parts should be assembled and the injector tested for proper opening pressure, spray angle and pattern. The bench test of injectors should incorporate the use of the fuel at the operating conditions where feasible. Injector nozzles not conforming to specified standards should be dispatched to a specialist workshop for reconditioning.

The VIT is not a temporary remedy for not pulling out a piston if indicated compression and combustion pressures are low. Manual adjustment of the VIT should be done only if a drop in maximum combustion pressure is measured across all cylinders, and subsequently supported by fuel quality tests results, whilst all other parameters being constant. These parameters include compression pressures, scavenge air temperature, fuel viscosity, amongst others. Condition monitoring of the operating parameters of the engine is the only justifiable means of envisaging manual adjustment of the VIT.

ANNEX—C

Fig. 4.1 Viscosity-Temperature-Pressure relationship curves (Courtesy of Mobil Oil Company Ltd.)

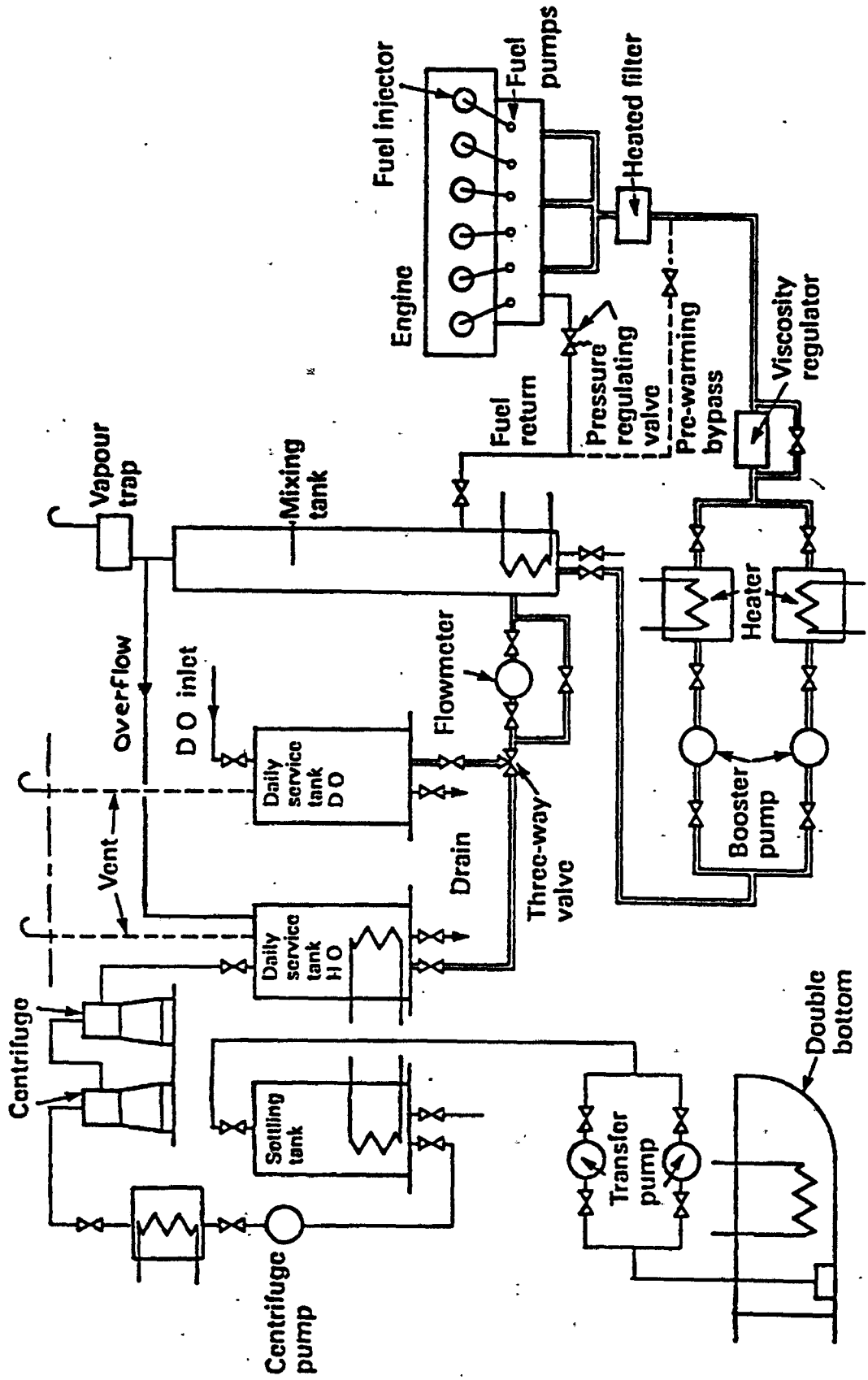


Fig. 4.2 Conventional Fuel Booster System

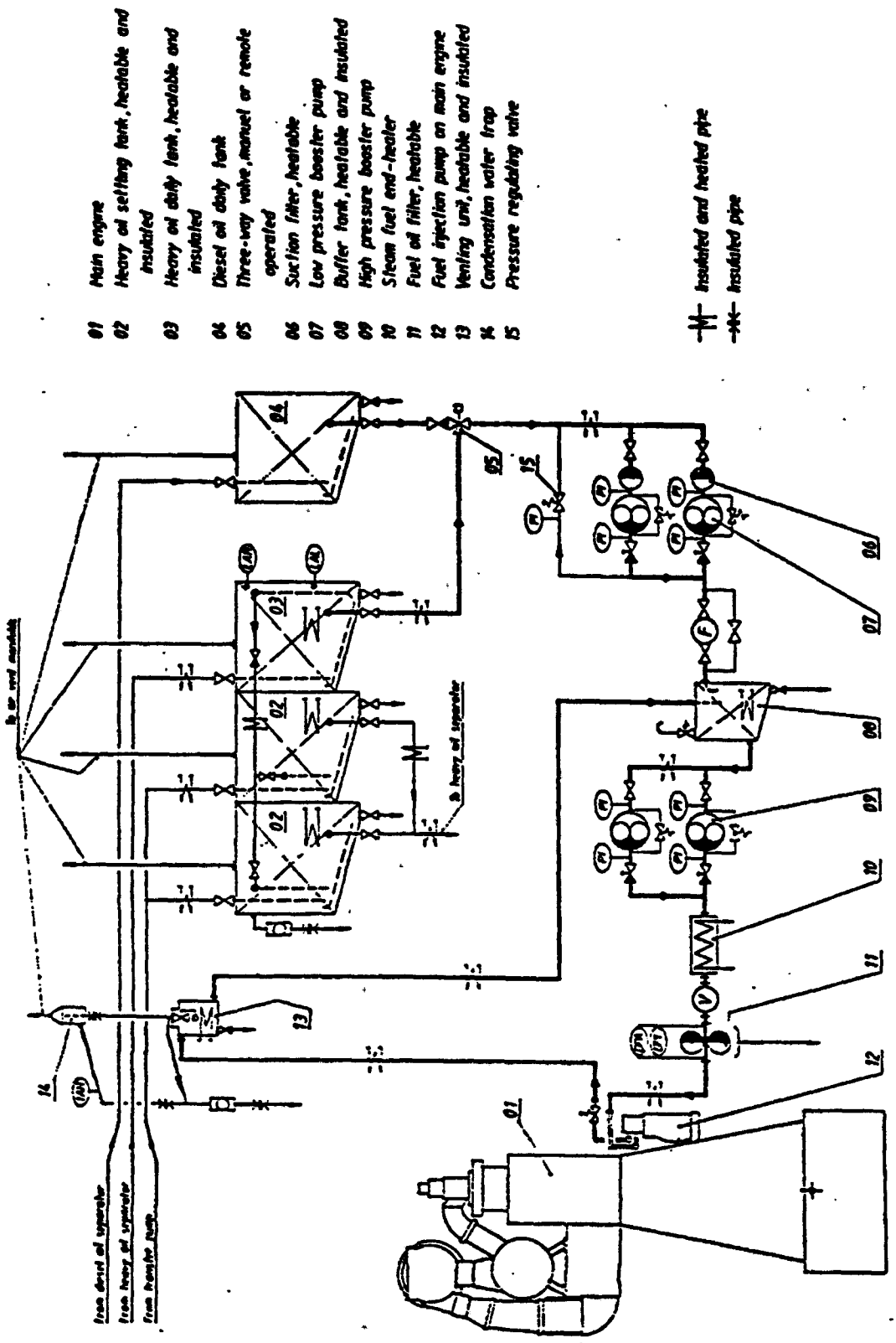


Fig. 4.3 Pressurized fuel system for Sulzer RTA-engines.
(Courtesy of Sulzer)

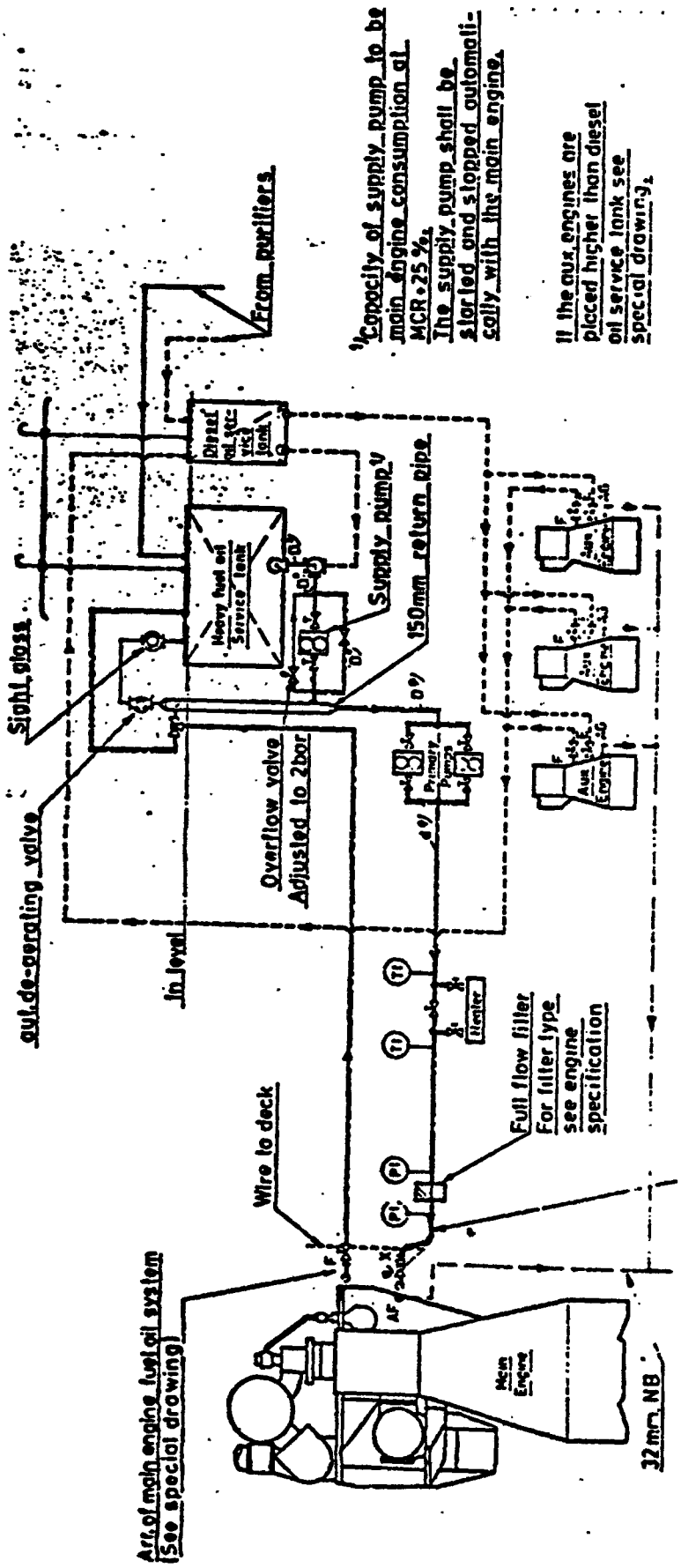
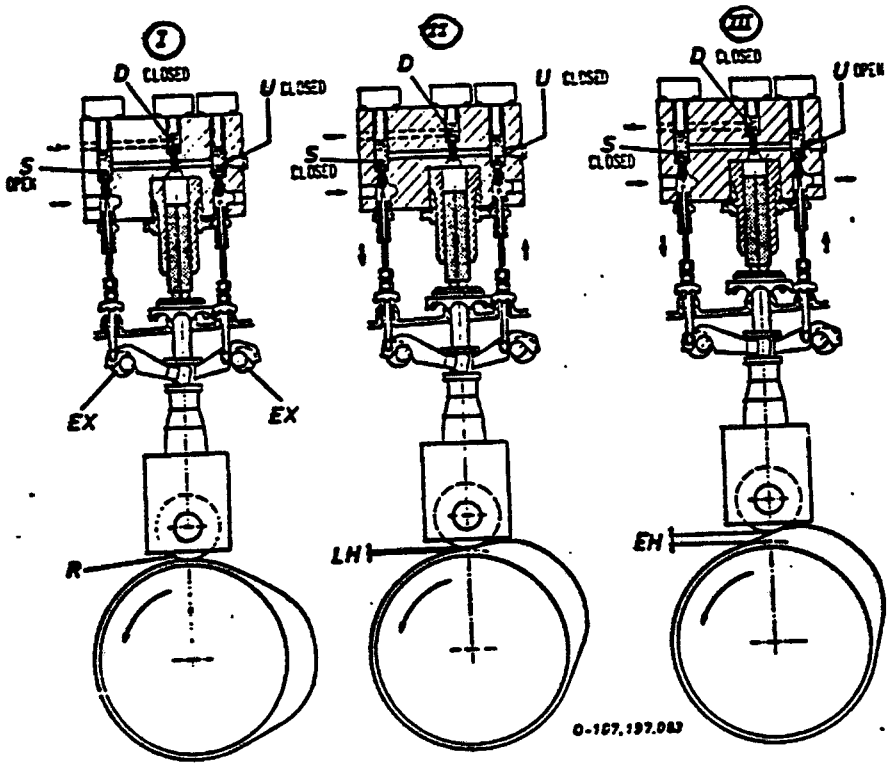
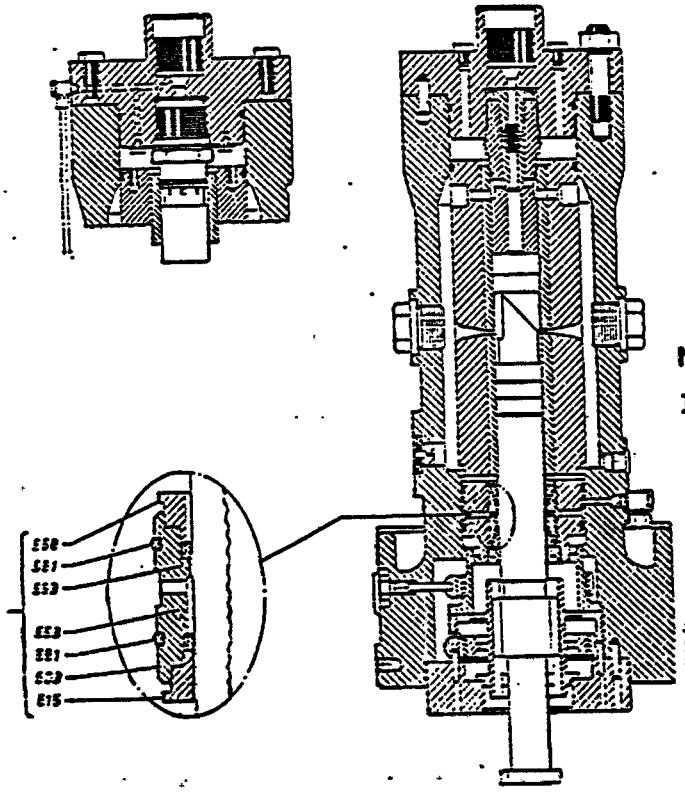


Fig. 4.4 Pressurized fuel system for MAN-B&W engines.
(Courtesy of MAN-B&W)



Sulzer's Fuel Injection Pump



MAN-B&W Fuel Injection Pump

Fig. 4.5 Sulzer and MAN-B&W Fuel Injection Pumps respectively

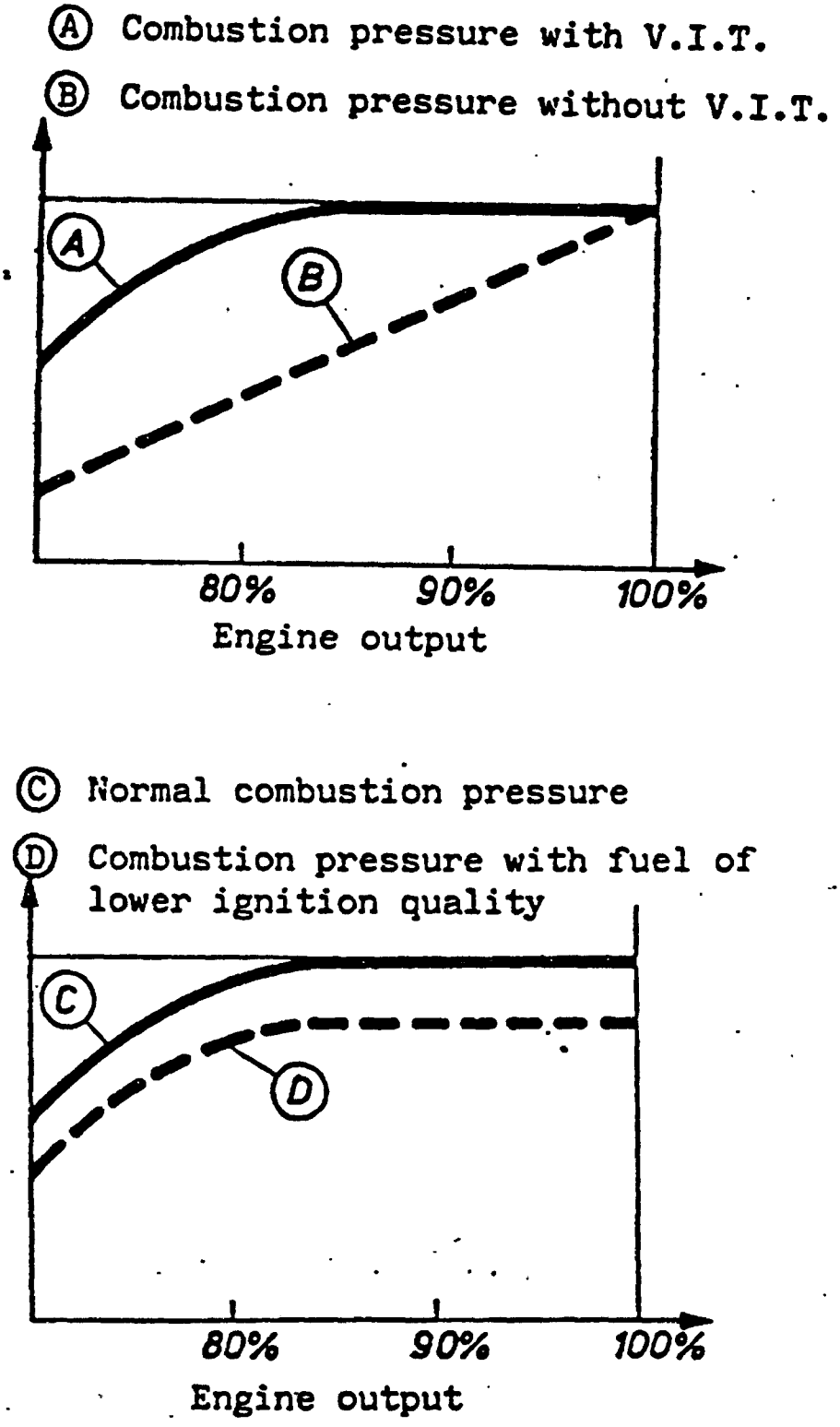
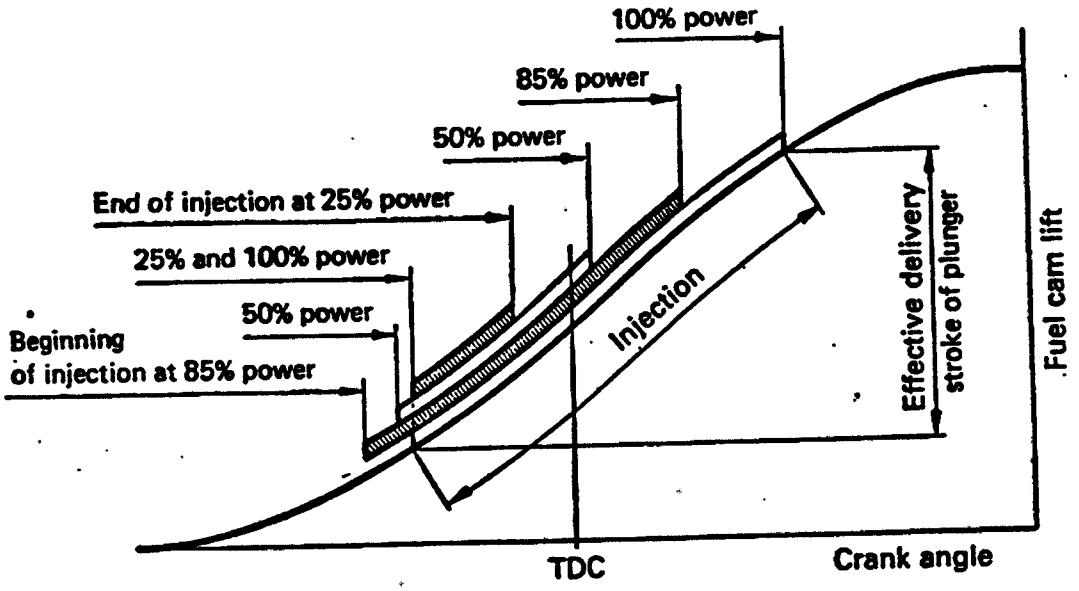
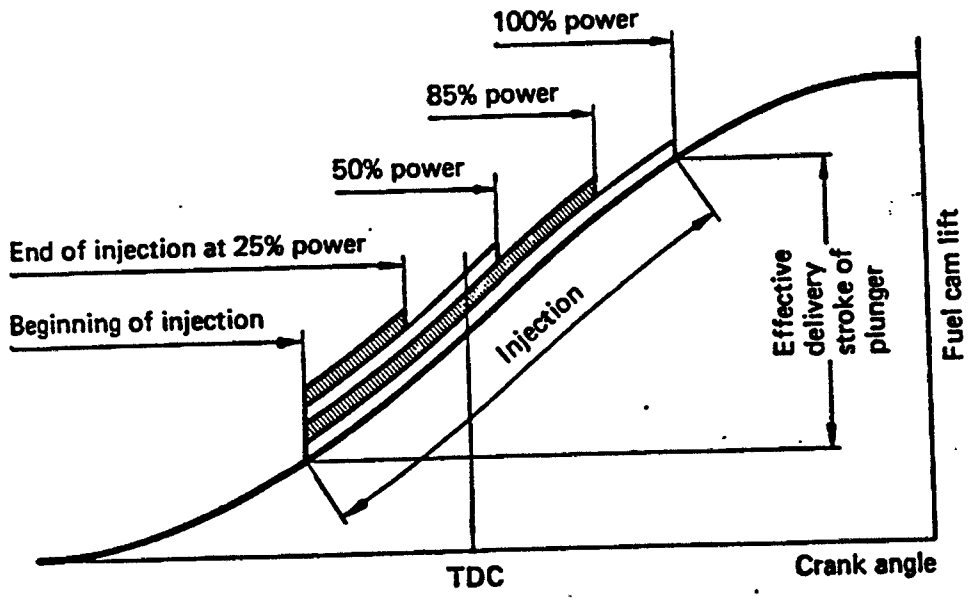


Fig 4.6 Variation in Combustion Pressure with VIT and Ignition Quality.

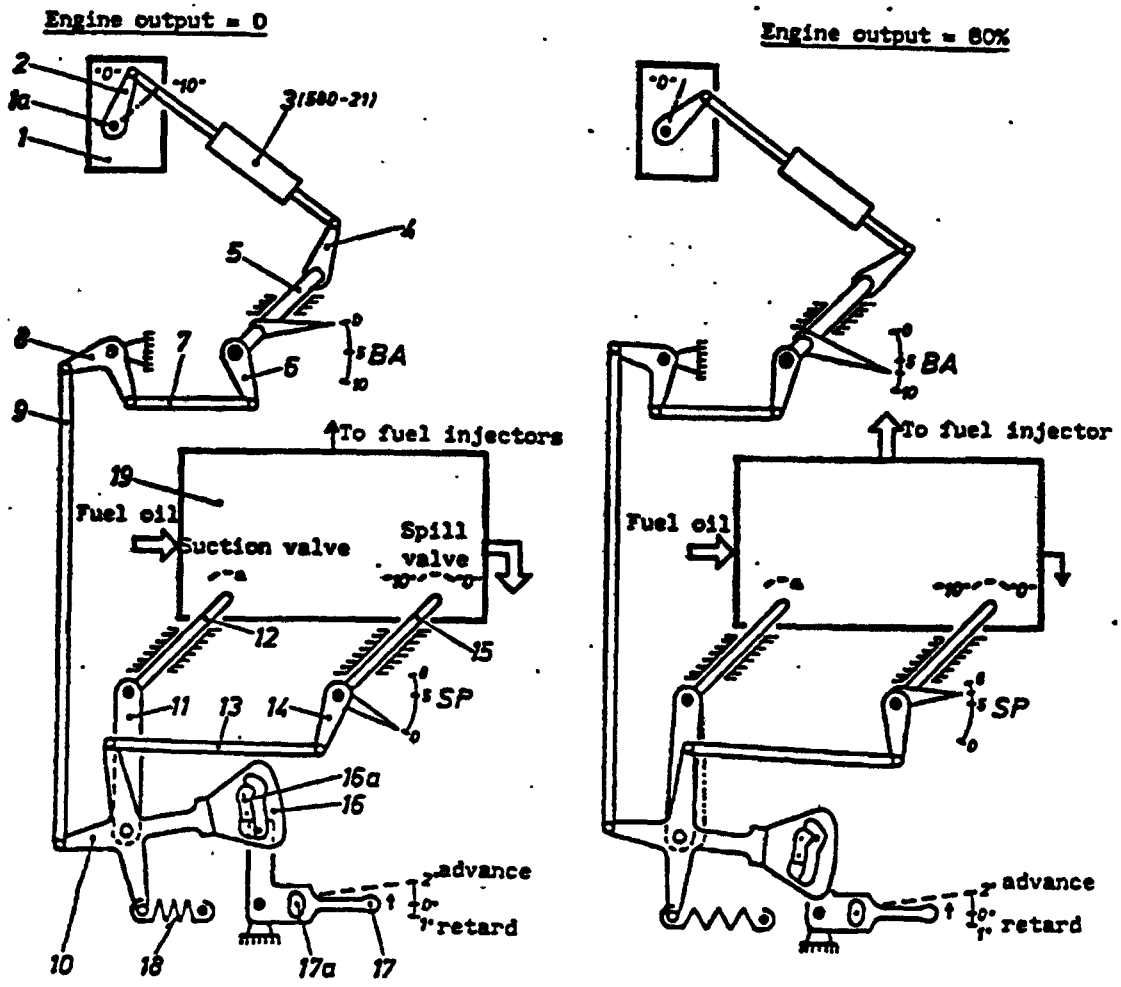


Fuel Injection Timing with VIT



Normal Fuel Injection Timing without VIT.

Fig. 4.7 Fuel Injection Timing Diagrams with and without VIT Control.



1 Speed governor
1a Governor output shaft
2 Lever
3 Air cylinder (see 580-21)
4 Lever
5 Intermediate regulating shaft
6 Lever
7 Adjustable rod
8 Dog lever
9 Adjustable rod
10 Dog lever
11 Suction valve regulating lever
12 Eccentric shaft for operating suction valve
13 Adjustable rod
14 Lever
15 Eccentric shaft for operating spill valve
16 Profile segment
16a Adjustable link
17 Setting lever for start of injection
17a Locking pin
18 Tension spring
19 Fuel injection pump

BA Load indicator
SP Setting scale

Fig. 4.8 Sulzer VIT System

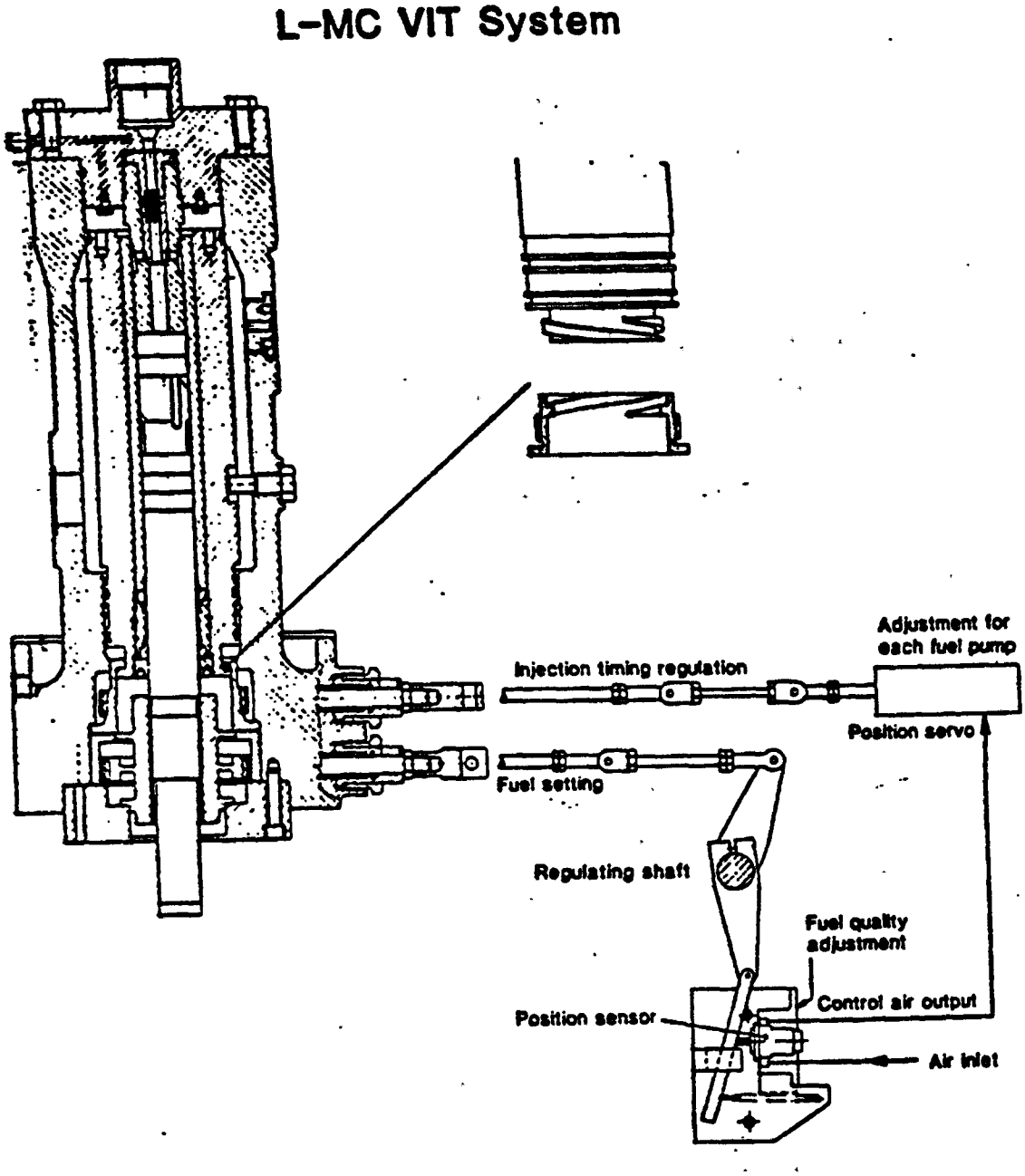
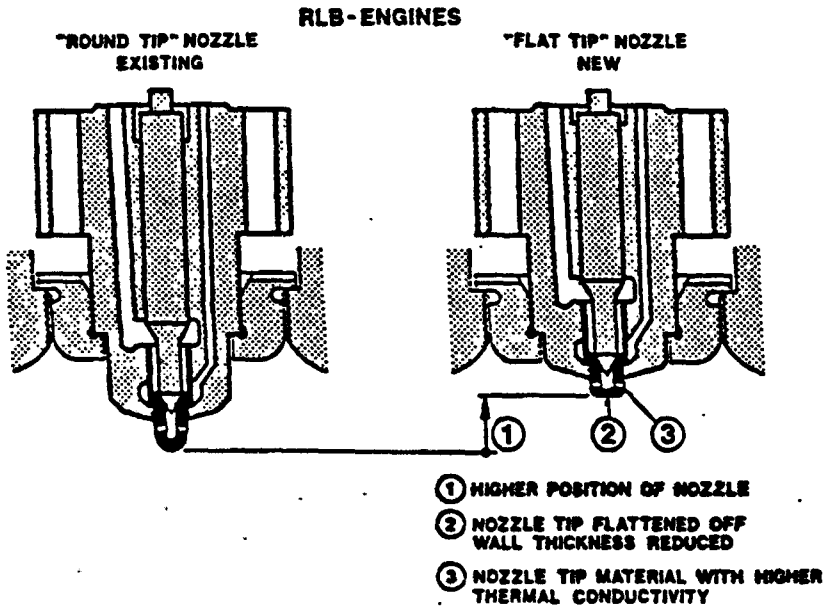
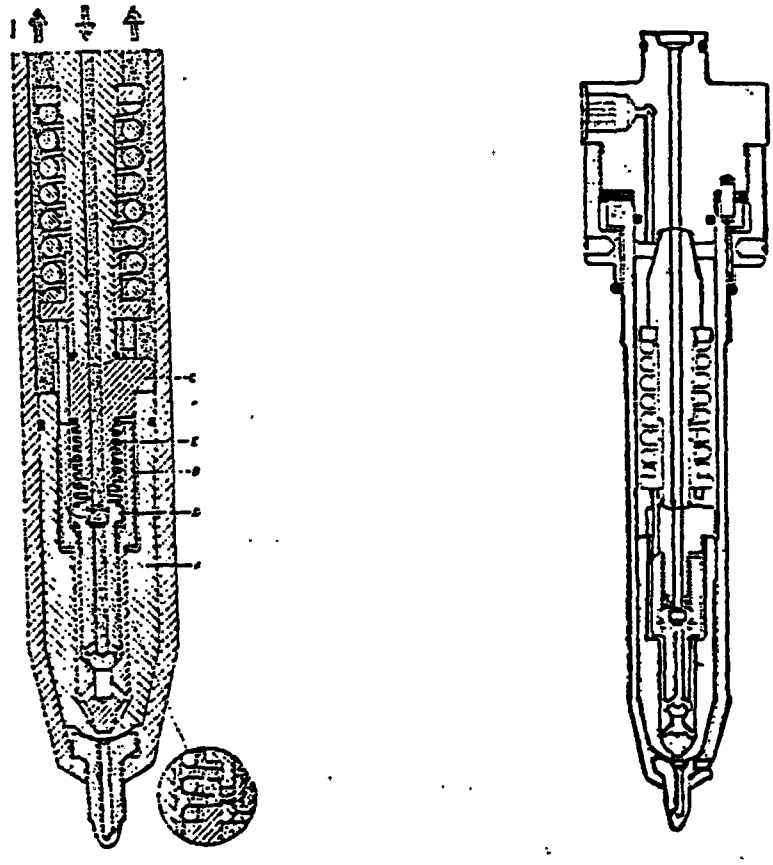


Fig. 4.9 MAN-B&W VIT System



Sulzer Water Cooled Fuel Injectors with the new Flat Tip for lower nozzle tip temperatures.



MAN-B&W Uncooled Fuel Recirculating Injectors at 0 engine rpm for HFO operation from berth to berth.

Fig. 4.10 Sulzer and MAN-B&W Fuel Injectors

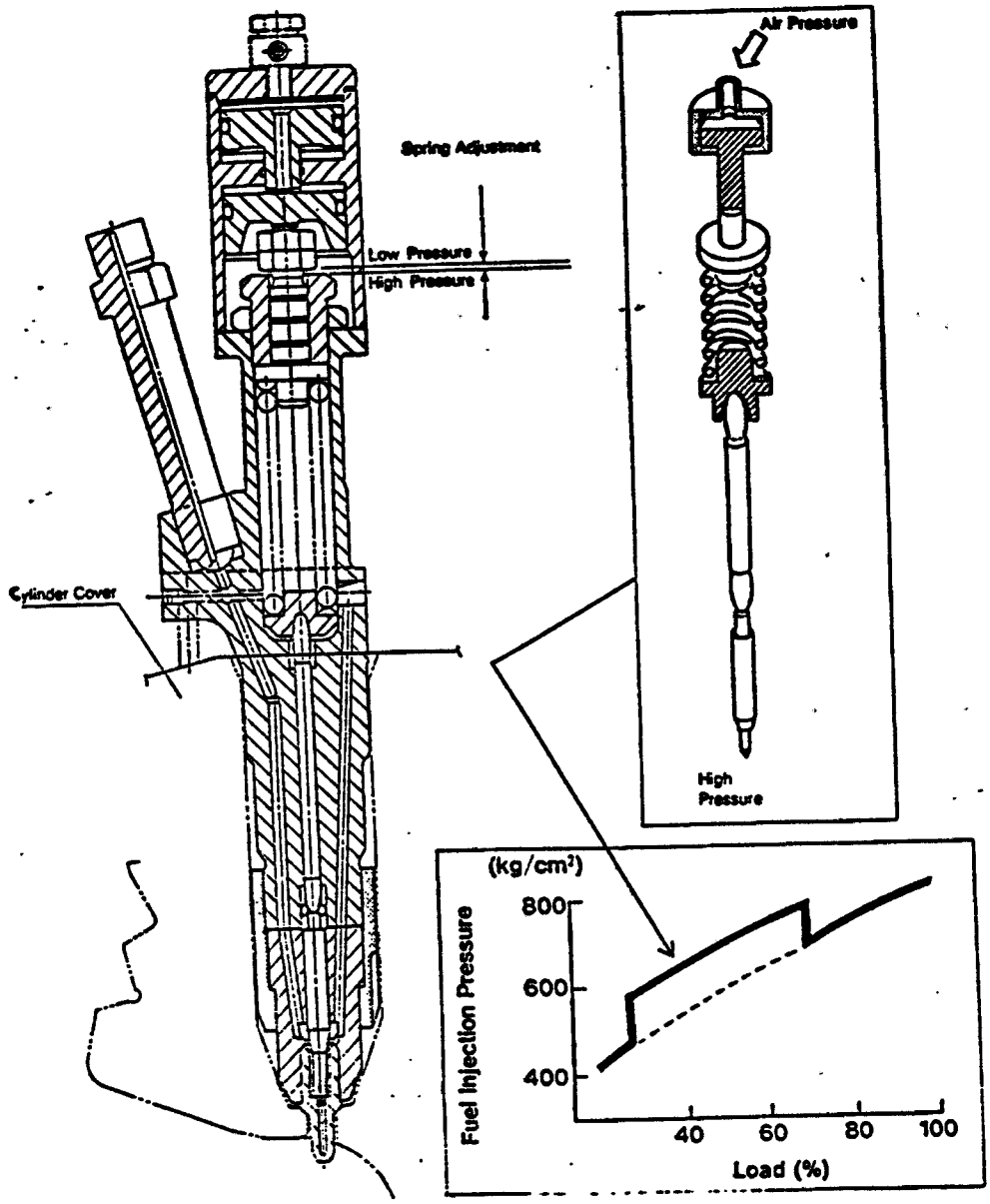


Fig. 4.11 Mitsubishi UE Diesel Engines Pressure Control Fuel Injector.

CHAPTER V

THE COMBUSTION OF HEAVY FUEL OIL (HFO) VERSUS THE SLOW SPEED TWO STROKE DIESEL ENGINE (SSD) AND EXHAUST GAS USER EQUIPMENT PARAMETERS

5.1.0 INTRODUCTION

In the wake of deteriorating qualities of HFO, the design and development of combustion chamber members and exhaust gas user equipment have improved steadily to accommodate poor quality fuels. This chapter will examine those designs and developments of the SSD combustion chamber members and exhaust gas user equipment as they influence the efficient combustion of HFOs. The effects of the various constituents of HFO on these members and equipment will be emphasized to underscore the need for an effective fuel management program.

There are many by-products formed during the combustion of HFOs. They range from a harmless single hydrogen atom to detrimental eutectic complexes. These by-products and their effects, as well as the preventive and corrective measures to combat them will be discussed. The controllable engine plant operational parameters and the need to maintain them as recommended will be mentioned.

The various forms of fuel related corrosion and wear of combustion chamber members and exhaust gas user equipment will be discussed. Operational and design aspects to

combat the latter will be mentioned. The developments in cylinder liner lubricating methods and lubricating oils as they relate to the reduction of fuel related corrosion and wear would be examined.

The maintenance of ideal conditions of combustion chamber members and exhaust gas user equipment is absolutely relevant for the combustion of HFOs. Thus, the effects of changes in the ideal condition as a result of fuel qualities and poor operational practices will be discussed. The delicate balance between scavenge air temperature and combustion chamber components with respect to the corrosive tendencies of HFOs will also be discussed.

5.2.0 THE SSD COMBUSTION CHAMBER DESIGN FACTORS FOR THE EFFICIENT COMBUSTION OF HFO

The combustion chamber is the limited area of the engine where the treated fuel is converted to thermal energy. The chamber is an enclosed zone which is bounded by the cylinder liner, piston and cylinder cover. These components must not only meet the thermal requirements imposed on them by the combustion process, but they also have to be designed to create the right conditions for the efficient combustion of the decreasing qualities of HFOs. Concurrently, they must withstand the acceptable debilitating effects associated with the burning of HFOs.

The drive to make the diesel engine more efficient in the wake of decreasing fuel qualities and increasing fuel prices, has moved the engine's thermal cycle closer to the ideal diesel cycle. To achieve this remarkable improvement, designers had to decrease the combustion/

compression pressure ratio. The compression pressure was significantly increased. Thus, a relatively higher temperature is available for the speedy ignition of the fuel.

The fuel injection process was optimized to allow for a reduced duration of injection, particularly in the four stroke engines and a more gentle pressure gradient between the compression pressure and the maximum combustion pressure. The optimum practicable heat release pattern was approached, barring the effect of ignition delay. The newer generation of slow speed two stroke engines operate with compression and combustion pressures up to 110 and 125 bars respectively with the S26MC engine reaching 135 and 160 bars respectively.

Newer SSDs have been designed with a single centrally located exhaust valve per cylinder. The improved use of exhaust gas potential energy by more efficient constant pressure turbochargers, and better design of scavenge air ports, have resulted in higher scavenge air pressures of plus 3 bars, and a cleaner cylinder air charge.

Larger stroke to bore ratios of about 3 or more have facilitated increased piston crown to cylinder cover distances, and subsequently a larger combustion space. The fuel charge is more centrally dispersed, thereby reducing fuel impingement on the cylinder liner, and poor combustion in the oxygen deficient outer periphery of the combustion chamber is avoided. Bore cooled combustion chamber members have also facilitated the use of the higher thermal cycle in the newer generation engines.

5.2.1 - CONSTITUENTS OF HFO AND THE COMBUSTION PROCESS

The combustion efficiency of a system is its ability to completely burn the combustible material with no residual detrimental effects or deposits. In the case of HFO, the combustion efficiency, whilst combustion chamber factors being ideal, depends greatly on the percentage composition of the various components found in HFO.

Carbon, as a constituent of HFO, accounts for about 87% by weight in the fuel. The reaction of carbon and oxygen in the combustion process to form carbon dioxide is a good measure of the combustion efficiency. Relatively high carbon dioxide content with low carbon monoxide content in the exhaust gas would suggest that good combustion had occurred.

Hydrogen on the other hand accounts for about 12% by weight in HFO. Although hydrogen is highly reactive in the combustion reaction, it plays a secondary role in accounting for the total energy of the combustion of HFO.

Sulphur contents in HFO has an upper value of 5% by weight. The reaction of sulphur in the combustion process produces relatively little amount of energy. Therefore, an increasing percentage of sulphur in HFOs will reduce the fuel net calorific value.

Ash forming components of HFO vary in origin, chemical structure and sizes, as well as their effects on engine components. Some of them may serve as catalysts in the production of detrimental products or as corrosive and

abrasive agents themselves. They may be insoluble in the fuel. Therefore, they should be removed by the treatment system. Unemulsified sodium in the form of sodium chloride and solid contaminants are the inferred insoluble components. On the other hand, vanadium and sulphur are soluble constituents of HFO. Thus, they must be dealt with from both the design and operational perspectives. See table V-1 for HFO combustion reactions and the products formed from these reactions.

Table V-1 REACTIONS FROM THE COMBUSTION OF HFO

FUEL COMPONENT	% BY Wt. IN FUEL	PRODUCTS FORMED	COMBUSTION REACTIONS	HEAT OF COMBUSTION (KCAL/Kg)
CARBON	85-87	CARBON DIOXIDE	$C + O_2 \rightarrow CO_2$	7,860
		CARBON MONOXIDE	$2C + O_2 \rightarrow 2CO$	2,480
		UNBURNED HYDROCARBONS	----------	------
HYDROGEN	10-12	WATER	$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$	34,050
SULPHUR	0 - 5	SULPHUR OXIDES	$S + O_2 \rightarrow SO_2$	2,211
ASH	0-0.1	VANADIUM OXIDES SULFATES COMPLEX VANADATES	----------	------

Courtesy of Drew Ameroid Marine

5.2.2 THE FORMATION OF SULPHURIC ACID AND LOW TEMPERATURE CORROSION

Sulphur is soluble in fuel. It can not be removed by the fuel treatment and conditioning process. The initial reaction of sulphur and oxygen in the combustion process produces sulphur dioxide which in itself is non-corrosive. A secondary inevitable reaction occurs. It is during this latter reaction that the sulphur dioxide molecule picks up an additional oxygen atom; hence, sulphur trioxide is formed.

As is evidenced by table V-1, water is an unavoidable product of combustion. It would exist as water vapor with a relatively low dewpoint compared to the existing surface temperatures of the combustion chamber members. However, sulphur trioxide reacts readily with water/water vapor to form sulphuric acid, especially in the presence of vanadium which serves as a catalyst to this reaction.

Sulphuric acid is very corrosive and the relative dewpoint of sulphuric acid is closer, and in some cases at the surface temperature of combustion chamber members. If combustion chamber members surface temperatures are allowed to reach the dewpoint temperature of this acid, particularly at the end of the exhaust phase, the phenomena known as 'low temperature corrosion' will begin. See table V-2 for the chemical process which leads to low temperature corrosion.

Table V-2 THE FORMATION OF SULPHURIC ACID IN THE COMBUSTION CHAMBER AND LOW TEMPERATURE CORROSION

$$S + O_2 \longrightarrow SO_2$$

Sulphur + Oxygen → Sulphur Dioxide

$$2SO_2 + O_2 \xrightarrow{V_2O_5} 2SO_3$$

Sulphur Dioxide + Oxygen → (Vanadium Pentoxide (catalyst)) → Sulphur Trioxide

$$SO_3 + H_2O \longrightarrow H_2SO_4$$

Sulphur Trioxide + Water → Sulphuric Acid

$$2H_2SO_4 + 2Fe \longrightarrow Fe_2(SO_4)_3 + 3H_2$$

Sulphuric Acid + Iron → Ferric Hydrogen Sulfate

For today's high output two stroke engines, low temperature corrosion is not only prevalent at the end of the exhaust phase. With the higher brake mean effective pressure (BMEP) of plus 15 bars at full load, the corresponding dewpoint of sulphuric acid is higher. The higher cylinder pressure would also enhance sulphuric acid penetration of the lubricating oil film on the cylinder liner wall (Shell Marine 52).

The use of higher sulphur content fuels, coupled with higher BMEP's, have significantly increased the condensation of sulphuric acid. Compounding the foregoing scenario is the thermal restrictions which cylinder liners and piston-ring zones must meet. To prevent these

components from cracking, loss of lubricating oil film and seizures at high engine loads, the inferred combustion chamber components temperatures must be kept below 200°C. At this temperature and relative pressure, the dewpoint of sulphuric acid could be reached.

To minimize the advent of low temperature corrosion, cylinder lubricating oil qualities were improved, and more advanced methods of cooling combustion chamber members have been employed. See fig. 5.1a for sulphuric acid dewpoint versus fuel sulphur content and combustion pressure.

5.2.3 VANADIUM AND HIGH TEMPERATURE CORROSION

Vanadium and vanadium compounds are the major proponents of 'high temperature corrosion'. High temperature corrosion occurs on combustion chamber members, predominantly the exhaust valve and piston crown. These two members operate at temperatures which would permit semi-solid ash compounds to adhere to their surfaces.

There are two critical temperatures at which an ash compound would pose problems for the combustion chamber members. The first temperature is the 'stiction temperature', and the other is the 'melting temperature'. The stiction temperature was defined by Wickert as, "the lowest temperature at which an ash deposit will fuse sufficiently to adhere to a non-corrosive metal surface in a controlled atmosphere" (Clark 23/5). The melting temperature of most ash compounds is about 20°C higher than the stiction temperature (Clark 23/5). See table V-3 for some of the ash compounds found in HFO, or formed

during the combustion process with their melting temperatures.

Table V-3 ASH CONSTITUENTS OF HFO AND THEIR MELTING TEMPERATURES

COMPOUND	FORMULA	MELTING POINT °C (ATM. PRESSURE)
Sodium Ferric Sulphate	$Na_3Fe(SO_4)_3$	540
Sodium Vanadyl Vanadate	$Na_2O.V_2O_4.5V_2O_5$	625-659
Sodium Meta-Vanadate	$Na_2O.V_2O_5$	630
Vanadium Pentoxide	V_2O_5	675-690
Sodium Sulphate	Na_2SO_4	880
Clacium Sulphate	$CaSO_4$	1450
Ferric Oxide	Fe_2O_3	1565
Silicon Dioxide	SiO_2	1720
Vanadium Tetraoxide	V_2O_4	1970
Aluminium Oxide	Al_2O_3	2650

Courtesy of Drew Ameroid Marine

Vanadium combines with sodium and sulphur during the combustion process to form eutectic compounds. These compounds will adhere to combustion chamber members with temperatures at or above the stiction temperature of the formed compound. These molten compounds attack the protective oxide layers on steel, thereby exposing the steel to corrosion and wear.

The most commonly formed eutectic is a combination of vanadium pentoxide and sodium sulphate. A eutectic mixture of 35% vanadium pentoxide and 65 % sodium sulphate has a very low stiction temperature, about 300°C. See fig 5.1b for vanadium pentoxide and sodium sulphate varying percentages mixtures with their stiction temperatures.

A severe form of high temperature corrosion occurs when resinous hydrocarbon compounds (asphaltenes) adhere to the valve seat and than trap solid ash compounds onto the surface. The constant pounding of the valve on the seat would than dent the sealing surfaces. This may result in a through channel across the sealing surfaces. This would induce valve leakage and subsequent burn out of the valve sealing surfaces would occur.

Another form of the above scenario is where the trapped solid ash compound would become molten due to exposure to high temperature combustion gases via the channel created. This molten compound would readily attack the valve metal and rapid corrosion would occur.

High temperature corrosion of non-sealing surfaces would give these surfaces a cobblestone look. These surfaces include exhaust valve stems and casings, cylinder covers, and turbocharger nozzle rings. This cobblestone

appearance of engine components is a signal of decreasing thickness and strength.

Besides their corrosive tendencies, eutectic complexes would plate out in the combustion and exhaust spaces, as well as in the turbocharger gas side. If this occurs, the affected component would require overhaul for the removal of these eutectic plates. These complexes could remain free in the combustion chamber, and their severe abrasive qualities could become pronounced on cylinder liners and piston rings.

For today's newer generation two stroke engines, high temperature corrosion is very remote from the inherent design features. However, it is the inevitable vanadium based ash compounds which contribute mostly to the wear of cylinder liners and piston rings. This phenomena occurs irrespective of the absence of catalyst fines, the presence of excellent lubricating qualities, and high scavenge air pressures.

5.3.0 CYLINDER LINER AND COMPONENTS OF HFO

Measurement of cylinder liner wear rates has traditionally been regarded as the parameter for indicating the operational performance of the engine plant. The measured wear rates and patterns can be classed into three main forms, namely, corrosive, adhesive, and abrasive wear. These various forms of wear are influenced by the fuel quality, its content of solid contaminants and the treatment/conditioning process, the fuel injection system, the temperature control of the combustion chamber members, and the cylinder liner lubricating oil distribution and quality.

Most operators would measure and inspect the cylinder liner during regular overhaul intervals. Unfortunately, severe wear due to any of these factors stated above would have already occurred. The measurements would only confirm the extent and nature of the wear.

Today, wear measurements of cylinder liners and piston rings can be done during the operation of the engine. This development, although not completely a new one, would certainly enhance on line diagnostics, as well as prolong components life span through immediate corrective actions by the operator.

Improved technologies in metallurgy and die-casting have produced liners of boron-alloyed cast iron. These liners have high resistance to wear, and excellent thermal load capabilities. Cylinder liner wear rates of 0.05mm/1000hrs are now feasible. More advanced methods of surface treatment for ferritic cast iron liners such as special nitriding surface treatment, tufftriding surface treatment, and laser surface hardening have not increased the service life of liners. Their use in slow speed two stroke engines is limited to the laser hardening prcess.

Therefore, designers had to inculcate the operational parameter of liner temperature control into the design as the first means of reducing fuel related wears. The upper limit at which cylinder liners and piston rings can operate without loosing the lubricating oil film has been tantamount in reducing adhesive wear, and high temperature corrosion. See fig 5.2 for typical combustion chamber members temperatures at MCR, and fig. 5.3 for optimum cylinder liner temperature range versus maximum combustion pressures with regards to corrosive and adhesive wears.

To establish an absolute control of liner temperatures, bore cooled liners were introduced. Insulating tube inserts of varying lengths installed in critical liner zones that are prone to low temperature corrosion, have insured that the liner temperature remained above the dew point of sulphuric acid. Although these design concepts are incorporated in the engine structure, it is the operator who must insure that the coolant temperature is kept at recommended values. See fig 5.4 for the Sulzer RTA liner with inserts and the corresponding cylinder liner wall temperatures.

It is inconceivable to design liners that would resist abrasive wear due to solid contaminants and catalyst fines found in the fuel. It remains the prime responsibility of the operator to guard against these contaminants entering the combustion chamber.

5.3.1 CYLINDER LINER LUBRICATION AND RELATED TRENDS TO COMBAT COMBUSTION CHAMBER WEAR

Cylinder liner lubrication is the second factor engine designers had to improve on in reducing fuel and nonfuel related wears. The higher BMEP made the already marginal single level lubrication more inadequate. The longer stroke brought about oil starved regions along the length of the liner as well as a decrease in the dynamic lubrication features due to the lower engine rpm.

Multilevel lubrication has been introduced and the distribution grooves configuration has been altered to facilitate an even distribution of oil along the entire circumference of the liner (see fig. 5.5a). Multilevel

lubrication also ensures that fresh oil is available at the top of the liner to neutralize acids formed during the combustion process. See fig. 5.6 for Sulzer multilevel cylinder lubrication features.

To ensure that lube oil is delivered at the right time and in the right amount over varying loads, a timed cylinder liner lubricating system was introduced. This load dependent lubricating system removes the somewhat debatable intervention by the operator in the lubricating process. This system would also ensure that lubricating oil film remains on the liner immediately after engine stoppage when sulphuric acid formation is likely. The precipitation of acid neutralizing calcium from the cylinder lube oil due to over lubrication, and its detrimental effects on exhaust valves and turbocharger turbine blades will be minimized by this system. See fig. 5.7 for the Sulzer mechatronic timed cylinder lubricating system.

5.3.2 CYLINDER LINER LUBRICATING OIL AND THE PRODUCTS OF COMBUSTION

Cylinder liner lube oils have been used continuously as the defacto for unusual wear of cylinder liners and piston rings. Convincingly enough, the major manufacturers of cylinder lube oils have kept pace with developments of diesel engines and fuel qualities. In cases where excessive combustion chamber members wear had been attributed to the quality of the cylinder lube oil, it was concluded that in most of these cases, the operator had erred in matching the grade of cylinder lube oil to the engine parameters and the qualities of fuels used.

Cylinder lube oils for HFO operation must be capable of neutralizing corrosive acids, preventing the build-up of deposits, and lubricating. The neutralizing quality of cylinder lube oils is indicated by its Total Base Number (TBN) measured in mgKOH/g. For SSDs a TBN 70 oil has proven satisfactory for fuels with sulphur content up to 3%. For fuel sulphur content above 3%, a TBN 100 oil is preferred. However, a new grade of cylinder lube oil with TBN 80 appears to have bridged the gap between these two extremes.

The decision to use the higher TBN oil should be preferred if the normal fuel consumed has a sulphur content above 3%. Prolonged or normal operation on low sulphur content fuels with relatively high TBN cylinder oils, would cause the unused neutralizing agent, mainly calcium, to solidify on the exhaust valves and turbocharger turbine blades.

To prevent the build up of deposits around the piston ring zones, metal detergents are used as additives to cylinder lube oils. These metal detergents provide alkalinity and detergency to clean up the by-products of incomplete combustion (The Motor Ship 06/90 12).

Cylinder lube oils must have high load-carrying capabilities and excellent oxidative stability. The conventional method of blending base stocks with bright stocks to increase the oil viscosity is more likely to make the oil thermally unstable. Due to this instability, rapid oxidation of the cylinder lube oil occurs near the top of the liner. As a consequence of the latter, microseizures and subsequent adhesive wear became prevalent in elder generation engines. With the higher

piston ring to liner loading found in newer generation engines, such phenomena would be catastrophic.

A new process of an all-mineral oil blended with heavy neutral base stock and advanced additives seems to have the qualities required for today's poor quality fuels and high output engines. Cylinder oil viscosities above 20 cST at 100°C with excellent overall qualities as synthetic oils is now possible. This is a plausible development with respect to wear reduction, cylinder lube oil cost, and the increased mean time between overhaul.

5.4.0 THE PISTON AND THE PRODUCTS OF COMBUSTION

The piston of diesel engines is subject to cyclic loads which require a rigid piston crown with excellent thermal conductivity. This combustion chamber component converts potential energy to kinetic energy. The design of the piston had to incorporate considerations of the decreasing qualities of HFO.

Those qualities of HFO which influenced the design of pistons are the corrosive constituents and the ignition quality. The ignition quality influenced the design of the piston crown geometry. The new geometry reduces the possibilities of fuel and flame impingement on the piston crown. Secondly, the strength of the piston crown was increased to accommodate the higher cylinder pressures. However, the effects of late ignition of poor quality fuels and the resulting higher pressure gradient was also considered.

Today, piston crowns are made of chrome molybdenum for increased strength. Some manufacturers install an 8mm

thick layer of Inconel 625 on the piston crown areas susceptible to high temperature and flame impingement (see fig. 5.5b). Although these design features are credible, they are intended for intermittent abnormalities. The operator must ultimately detect abnormalities timely enough and take corrective actions.

The corrosive constituents, primarily of the soluble type, are responsible for high temperature corrosion of the piston crown. Effective bore cooling of the piston crown has significantly reduced this form of corrosion. The effectiveness of this design depends on the operator's ability to maintain the coolant temperature within the recommended values as per engine loads.

Chromium plating of the ring groves, particularly the top ring grove offers minimum resistance to wear induced by catalyst fines and eutectic ash complexes.

5.4.1 PISTON RINGS

The piston ring is the complex component of the combustion chamber whose functions and qualities are dictated by many factors. The design of piston rings encompasses considerations of the wear rate with respect to the cylinder liner and the piston ring grove, the mechanical load capabilities and thermal conductivity, the corrosion resistance characteristics, as well as its embeddability.

From the perspective of the combustion of HFO the piston ring is an indirectly cooled component. Therefore, an excellent thermal conductivity is required to transfer heat to the liner and piston. This feature would augment the rings residual corrosion resistance by maintaining its

temperature between the range of low and high temperature corrosions. Thermal fatigue would also be avoided.

The embeddability characteristics of the piston ring is essential in reducing scuffing and scoring of the liner. This detrimental phenomena is accelerated by the presence of FCC fines and other solid ash components. Secondly, microseizures occurring at the top of the liner will produce hard microwelds of dislodged combustion chamber members fragments. These microwelds, along with solid fuel contaminants, could promote excessive abrasive wear and seizures as well as induced corrosive wear of cylinder liners and piston rings.

It is again pertinent to assert the operators role in correlating fuel quality tests results with the fuel treatment plant and engine operational parameters adjustments. The proper matching of cylinder lube oil to the fuel quality and the engine rating, as well as selecting the right piston ring as per the engine manufacturer's recommendations should never be compromised. Piston rings are the easily disposable components of the combustion chamber. However, the rings integrity between planned overhauls can only be assured by adapting all of the above considerations.

5.5.0 EXHAUST VALVES

Exhaust valves used on slow speed two stroke diesel engines are predominantly of the single large centrally located type. Their development to withstand the harsh environment in which they operate, including deteriorating fuel qualities, is a continuous process. The increasing

demand for longer valve mean time between overhaul is no exception to the process.

Currently, there are several valve materials being used. Austenitic and martensitic steel valves with varying grades of stellite hardfacing are used extensively in elder generation engines. Nimonic 80A valves without hardfacing and nimonic 81 valves with hardfacing materials of deloro alloy 60 and colmonoy 6 respectively are being used in the newer generation of engines.

Nimonic valves have proven to have a respectable operational span with heavy fuels. This feature is enhanced by the close proximity of the cooling water to the valve seat sealing surface. Bore cooling of the valve seat has lowered the valve sealing surfaces temperatures below the point of high temperature corrosion.

The new design of exhaust valves allow the valve head (flange) to be rotated by the exhaust gas when the valve is open. The rotation of the valve head continues until it is firmly closed against the seat. At the initial stage at which the valve head makes contact with the seat, the valve head is still rotating. This feature provides a grinding action between the valve head and seat. Any contaminant trapped between the sealing surfaces will be dislodged and blown away prior to the complete closing of the valve. Secondly, any hot spot which has developed on the valve sealing surfaces will not occur at the same point on successive strokes.

The exhaust valve cage has been subjected to cold corrosion in way of the gas duct. Excessive cooling of the cage was primarily responsible for this. Better

design of the cooling chamber, and in some designs, uncooled valve cage around the exhaust gas duct area, have virtually eliminated this problem.

Difficulties encountered with exhaust valves in regards to the constituents of HFO were discussed in section 5.2.4. The controllable operational parameters are similar to those already mentioned. However, the operator should routinely confirm that the exhaust valve is rotating. See fig 5.8 for design features of exhaust valves.

5.6.0 CYLINDER COVERS

Cylinder covers have not been a major problem item with respect to the combustion of HFO. Their basic design had to incorporate detailed thermal and mechanical stresses analysis to account for the many openings available for combustion chamber accessories. The geometry of the combustion chamber side had to be shaped to improve the combustion process. Bore cooling of cylinder covers has virtually eliminated the prospect of corrosion and severe pitting.

5.7.0 TURBOCHARGERS AND THE COMBUSTION OF HFO

The turbocharger turbine blades, nozzle rings and exhaust gas casings are susceptible to corrosion and pitting from the eutectic complexes formed during the combustion of HFO. There are several operational factors which would also increase the formation of blade deposits. If the engine is overloaded, or the inlet air to the cylinder is restricted, the exhaust gas temperature will rise. This will lead to increased deposit formation.

Incorrect use of the VIT to correct engine components deficiencies could unintentionally lead to engine overload. Poor combustion in one or more cylinders due to defective injectors could also accelerate the process of deposit formation. Blocked scavenge air ports in loop scavenge engines as well as dirty air intake filters and charge air coolers air sides will decrease the air/fuel ratio, with a subsequent increase in the exhaust gas temperature.

Contaminants from the combustion of HFO, such as sodium salts and other eutectic complexes, coupled with metallic additives from unconsumed cylinder lube oil, are all contributory factors to deposit formation. Deposit layers of vanadates and sodium sulphates are the frequently occurring formation on exhaust gas user equipment.

Sodium salts act as the bonding element in most of these deposits. Planned and frequent water washing or steam injection of the turbocharger gas side would dissolve the bond. However, carbonaceous deposits would require chemical solvent or manual cleaning. Solid particle injection would do well if the deposits have solidified.

High temperature corrosion of the turbocharger blading is unlikely. The expansion of the exhaust gases through the turbine lowers the gas temperature. Secondly, the stiction temperatures for most ash compounds are higher than the average 380-300°C encountered across the turbine blades. The one exception is the eutectic mixture of 2:1 sodium/vanadium ratio. In this case, the stiction temperature would be in this range.

Low temperature corrosion is possible when operating at very low loads or during maneuvering. Blade deposits may also absorb sulphur trioxide from the gas stream immediately after shut-down. Cold corrosion and erosion of nozzle rings and exhaust gas casings have also been prevalent. Controlled cooling of the exhaust casing and uncooled casings have kept this component temperatures above the dew point of corrosive compounds.

5.7.1 TURBOCHARGER EFFICIENCY AND CHARGE-AIR IN THE COMBUSTION OF HFO

The turbocharger efficiency has increased steadily from about 50% to 70%. The designs have improved to a point where pressure ratios of up to 4:1 are achievable in single stage turbocharging. These developments have increased the cylinder air charge pressure with a corresponding increase in the compression pressure.

The combustion chamber can be better liberated of exhaust gases. The configuration of the charge-air ports in the cylinder liner has certainly increased the sweeping action in the combustion chamber. Higher air/fuel ratios are now possible. The increased turbulence which is facilitated by better scavenge air ports design and the higher charge air pressure, has ensured proper air/fuel mixture in the combustion chamber.

It is absolutely imperative to maintain these positive features of the turbocharger if poor quality fuels are to be burnt efficiently. Deposit formation on turbocharger turbine blades would certainly decrease the turbocharger efficiency rapidly. Dirty intake air filters and

compressor blades as well as choked air coolers air sides are all contributory factors to insufficient air supply to the combustion chamber.

The differential pressure gauges installed on the air filters and coolers should be maintained in excellent condition. Readings from these gauges would provide valuable information regarding the condition of these components. Routine cleaning of the compressor blades should be done as per the manufacturer's instructions.

5.7.2 CHARGE AIR TEMPERATURE RELATIVE TO THE COMBUSTION OF HFO AND CORROSION

The charge air temperature before the combustion chamber affects the ignition delay time and the formation of corrosive compounds. The appropriate temperature of the charge air is certainly governed by the relative humidity, the dewpoint of water vapor and the engine load.

When operating in humid conditions the water content in the air is very high. Up to two tons of water per ton of fuel burnt could be in the charge air. If the engine is operating at full load the charge air could be cooled below the dew point. In this case almost all of the water can be separated out of the air. For modern engines fitted with VIT and charge air-water separators, this is a plausible development. The former feature can compensate for ignition delay associated with the cooler charge air, while the other would assure the effective removal of the water in the charge air. Adequate drainage for the separated water should be provided.

On the contrary, if the engine is operated at significantly reduced loads, the charge air temperature could be kept above the dew point of water vapor. If the engine is fitted with charge air heaters, than the charge should first be cooled to remove the water prio to heating. This would help to reduce ignition delays. The combustion chamber members temperatures and the exhaust gas temperature will be correspondingly higher. Low temperature corrosion can thus be avoided.

The dilemma in selecting the right charge-air temperature is not as easy as was stated. The proper selection of the correct charge-air temperature requires an astute operator to balance the interdependence of engine load, fuel ignition quality and VIT adjustment, fuel sulphur content and cylinder oil feed rate, as well as combustion chamber members temperatures.

When the charge-air is heavily salt laden the water should be separated from the charge-air irrespective of the fuel vanadium content. Operating at or near the dewpoint of the water vapor should be avoided. The tendency for this damp air entering the combustion chamber and washing off the cylinder lubricating oil film is very likely.

Operators should use the supplied relative humidity-scavenge air pressure/temperature charts to determine the optimum air temperature range with respect to the engine manufacturer's recommendations.

5.8.0 WASTE HEAT BOILER AND STACK CORROSION

The corrosion of waste heat boiler tubes from the exhaust side and the stack is directly related to sulphuric acid formation. The exhaust gases temperature after the turbine is normally higher than the dewpoint of sulphuric acid, except at low loads. If the waste heat boiler circulating water temperature is too low, the exhaust gas temperature could be lowered significantly as it passes through the tube banks. Low temperature corrosion of the boiler tubes and stack would occur. Low exhaust gas temperatures in the waste heat boiler and stack due to inefficient plant operation should be avoided.

Accumulated soot on the boiler tubes would absorb sulphur trioxide. If this accumulated soot enriched with sulphur trioxide is not blown off the tubes, corrosion would occur when the dewpoint is reached. Frequent soot blowing of the waste heat boiler tubes is obviously necessary from the standpoint of efficiency, but it is equally important for the prevention of corrosion.

Prior to maneuvering the waste heat boiler tubes should be blown free of soot. When the engine is not running the circulating water to the waste heat boiler should be maintained at temperatures above the dew point of sulphuric acid.

ANNEX–D

Fig. 5.1a The influence of fuel sulphur conmtent and combustion pressures on the dew point of sulphuric acid.

Fig. 5.1b Stiction temperature of eutectic complexes versus sodium sulphate and vanadium pentoxide ratios.

Fig. 5.2 Combustion chamber temperatures at full load

Fig. 5.3 Optimum cylinder liner surface temperature versus P-max with respect to corrosion and adhesion

Fig. 5.4 The Sulzer RTA bore cooled liners with inserts, and surface temperature versus the dewpoint of water

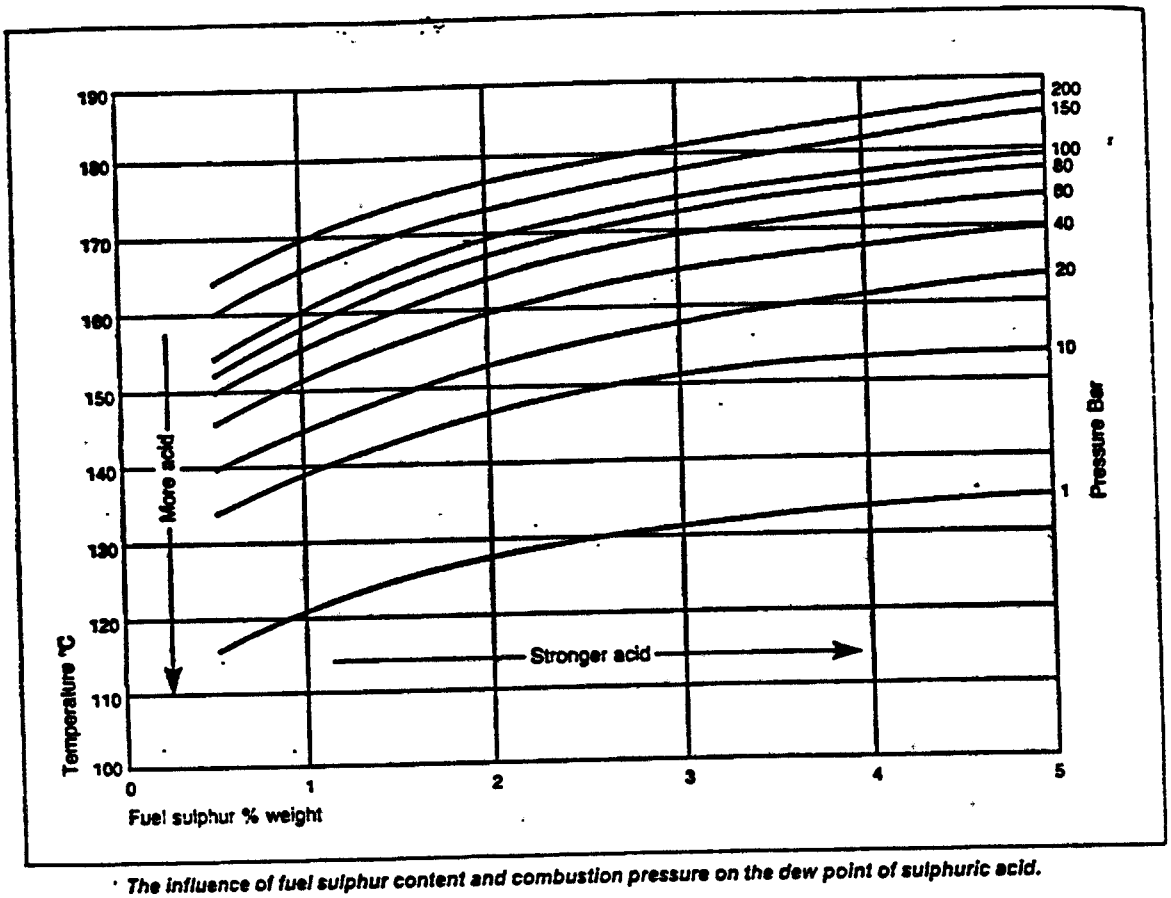
Fig. 5.5a Sulzer improved cylinder oil distribution grooves

Fig. 5.5b MAN-B&W Bore cooled piston crown with Inconel 625 high temperature protection layer

Fig. 5.6 The Sulzer RTA multilevel cylinder lubrication, and relative oil film thickness

Fig. 5.7 Diagram for timing injection of cylinder oil by mechatronic

Fig. 5.8 Design features of exhaust valves



The influence of fuel sulphur content and combustion pressure on the dew point of sulphuric acid.

Fig. 5.1a Source: Shell Marine. Lubricants and Fuels in Ships. pg. 54.

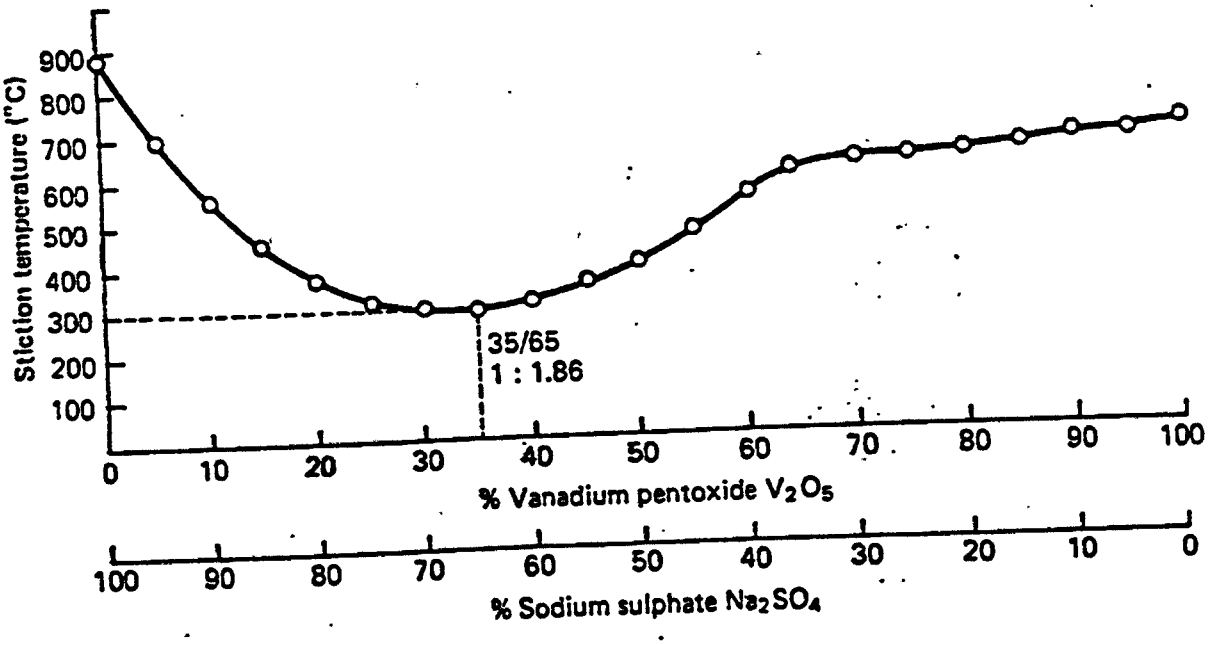
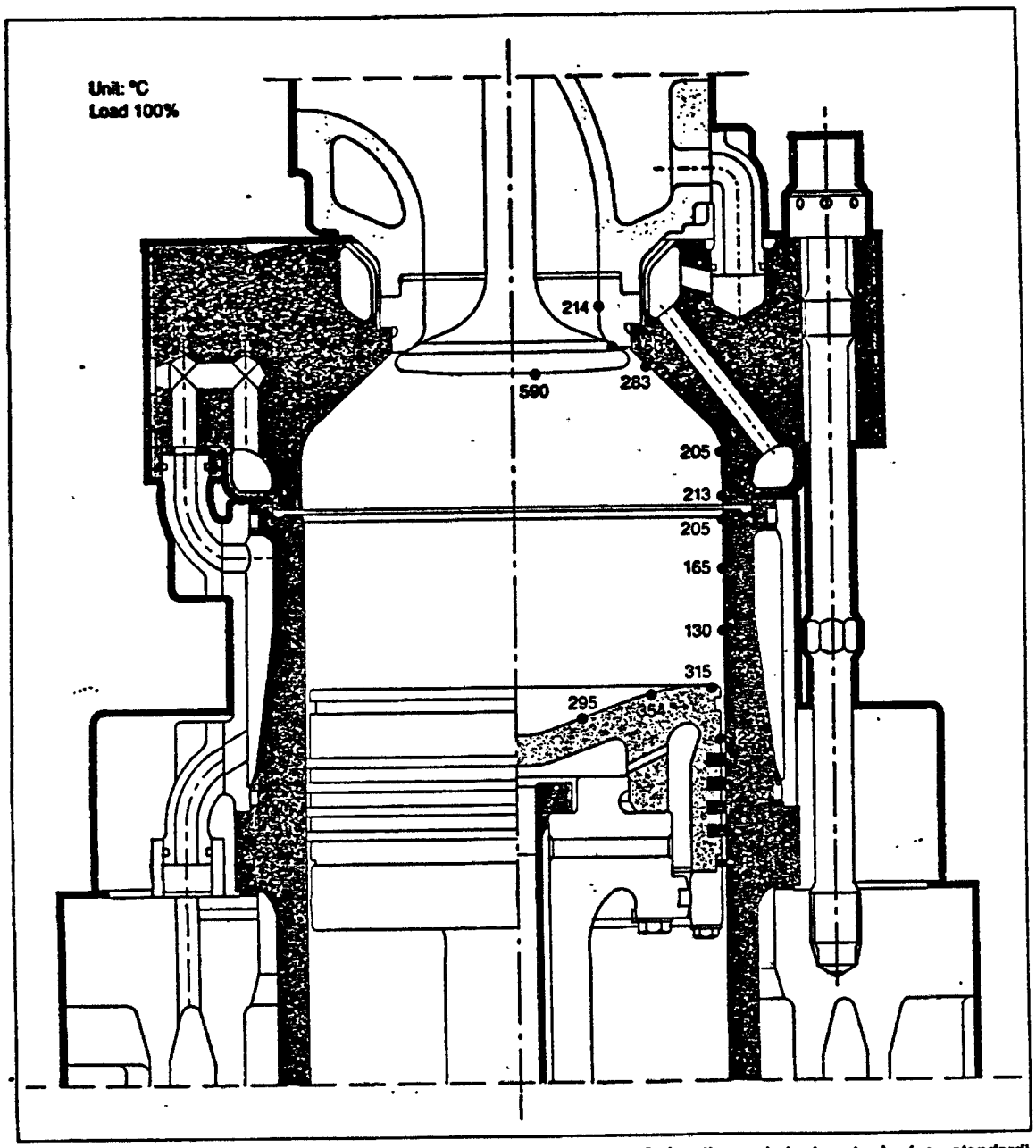
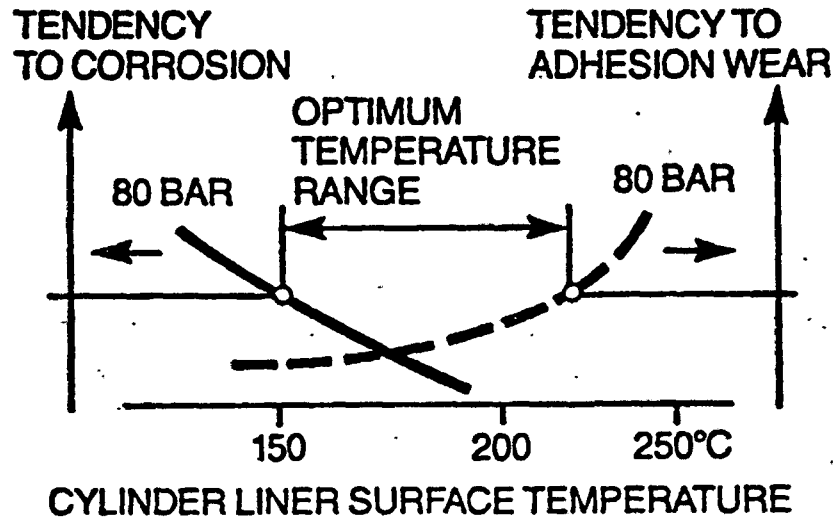


Fig. 5.1b Source: George H. Clark. Industrial and Marine Fuels Reference Book. pg. 23/5.



MAN-B&W L35MC combustion-chamber temperatures at full load. (Before the cooled exhaust valve (now standard) was incorporated).

Fig. 5.2 Source: Shell Marine. Lubricants and Fuels in Ships. pg. 32.



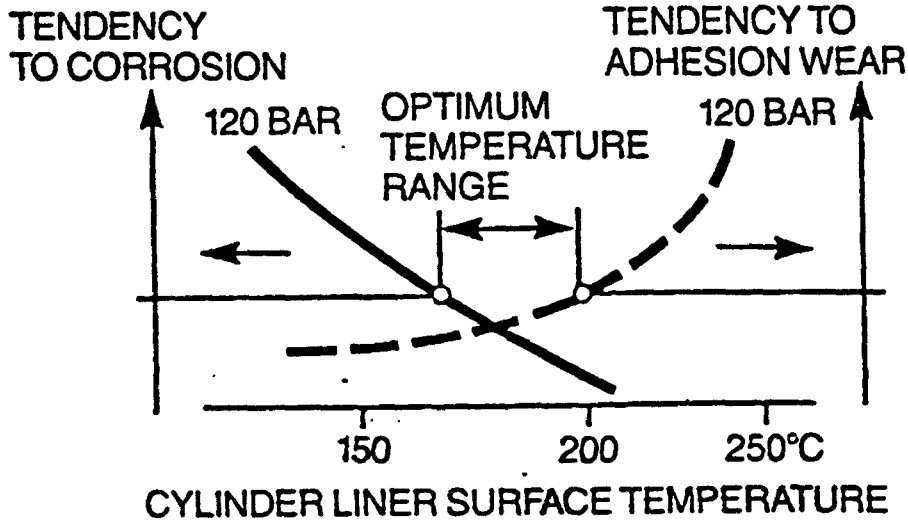
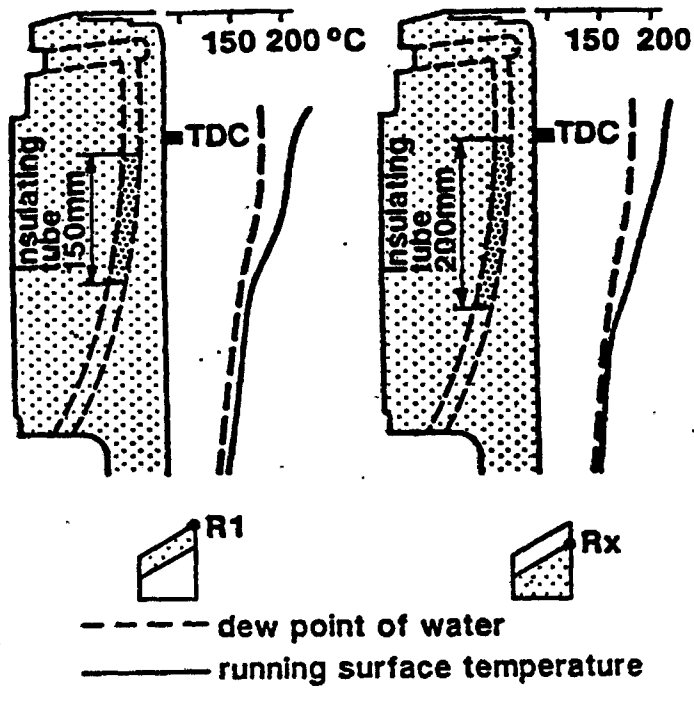
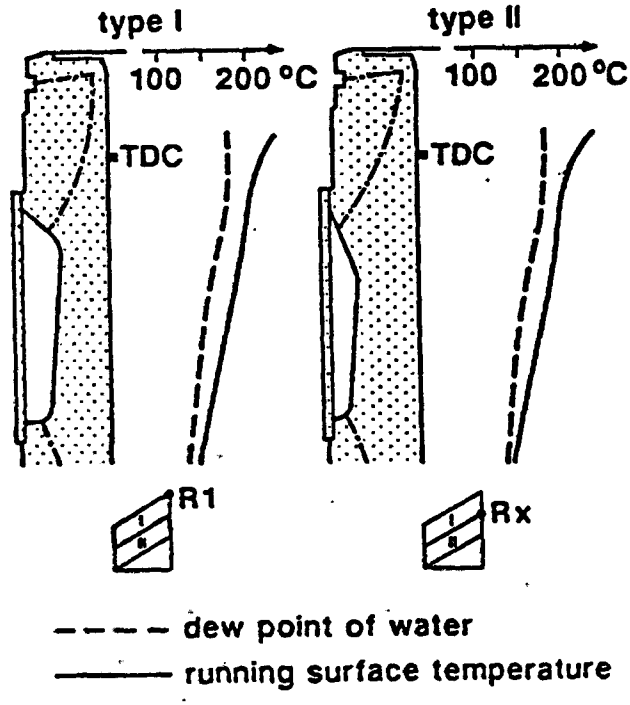


Fig. 5.3 Optimum cylinder liner surface temperature versus P-max with respect to corrosion and adhesion.

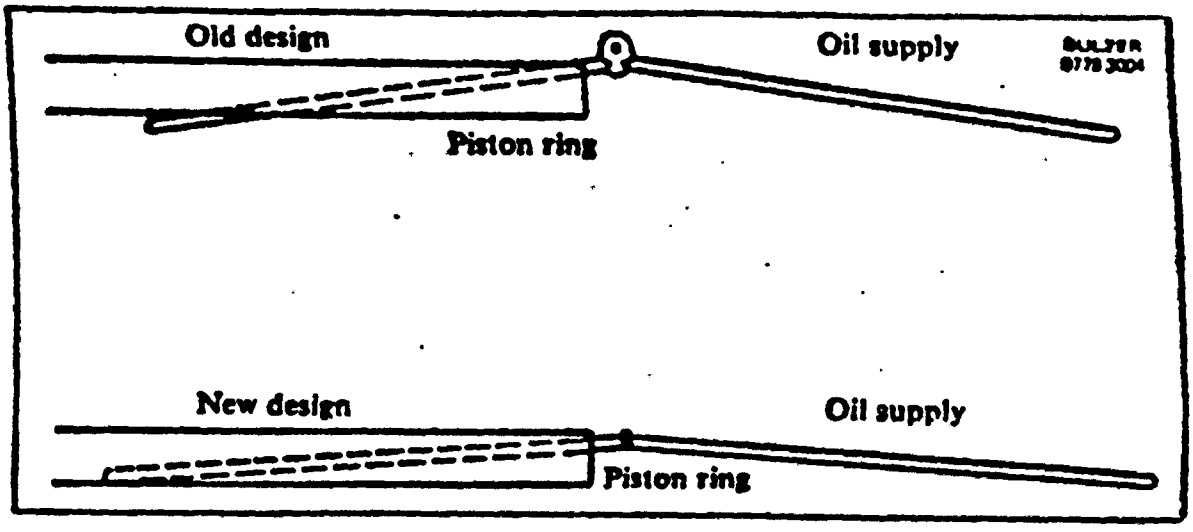


Cylinder liner surface temperatures are kept above dew point by inserting different lengths of insulating tubes according to the engine rating (R1 and Rx)



Typical liner surface temperature distributions with short-collar liners. The two types of short-collar liners for RTA.2-series engines match the engine cooling requirements in the respective zones of the layout field: type I for the upper zone and type II for the middle, with the bottom zone using a type II liner fitted with insulating tubes

Fig. 5.4 The Sulzer RTA bore cooled liners with inserts, and surface temperature versus the dewpoint of water (courtesy of Sulzer Bros. Ltd.).



Oil distribution grooves in the cylinder liner.

Fig. 5.5a Sulzer inproved cylinder oil distribution grooves (Courtesy of Sulzer Bros. Ltd.)

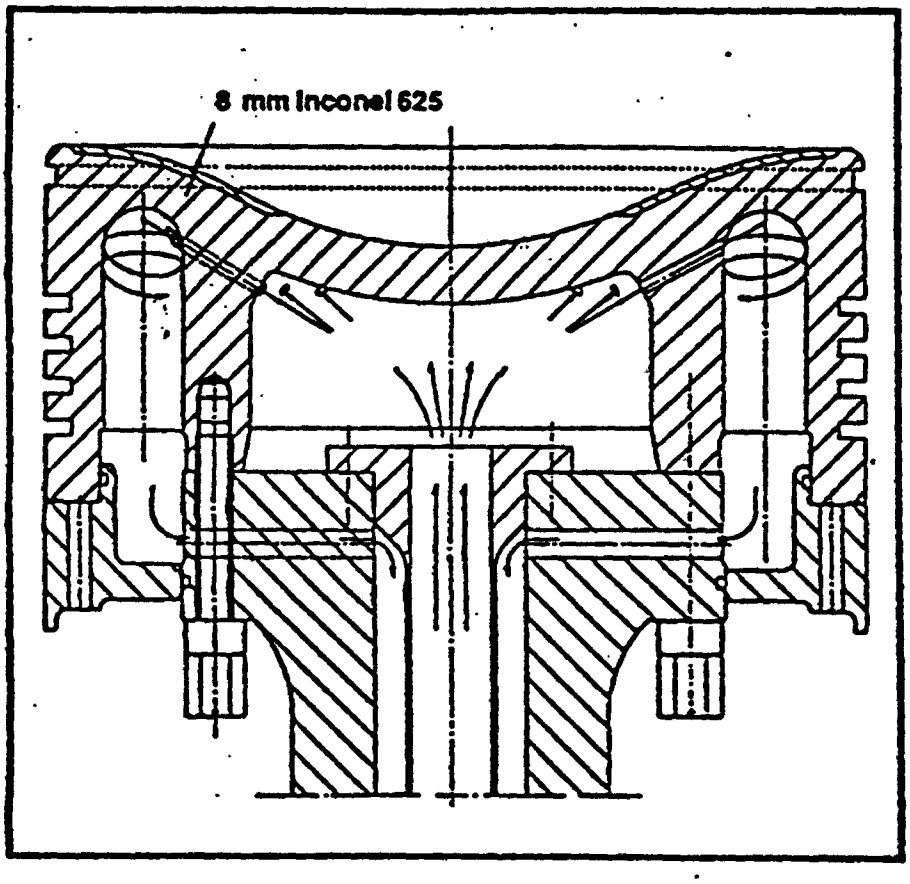
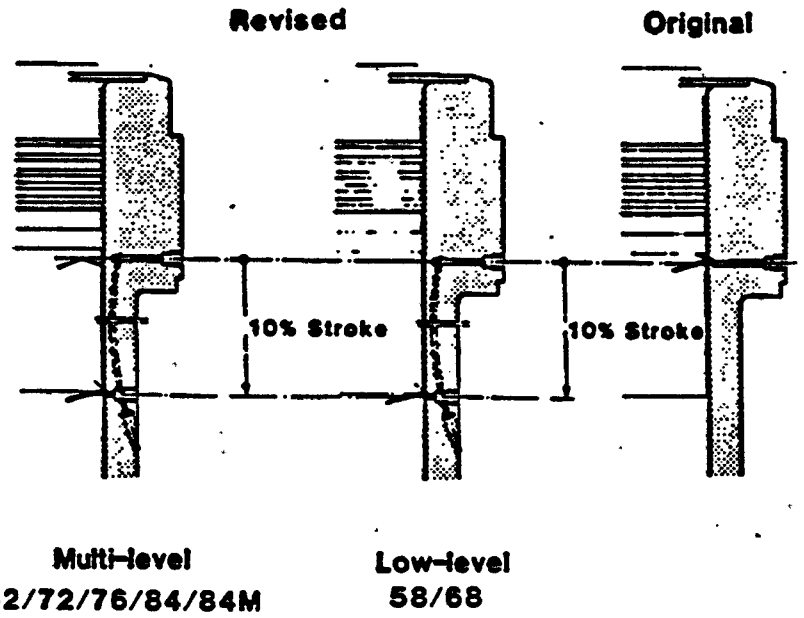


Fig. 5.5b MAN-B&W bore cooled piston crown with Inconel 625 high temperature protection layer (courtesy of MAN-B&W).



Position of lubricating oil quills and grooves in RTA cylinder liners for low-level and multilevel lubrication

The superior performance of multilevel cylinder lubrication is shown by these results from the Sulzer LUB programme. Compared with single-level lubrication at A or C, the multilevel lubrication gives an optimum combination of oil film thickness throughout the stroke, but especially in the upper region and a high oil refreshing rate near TDC

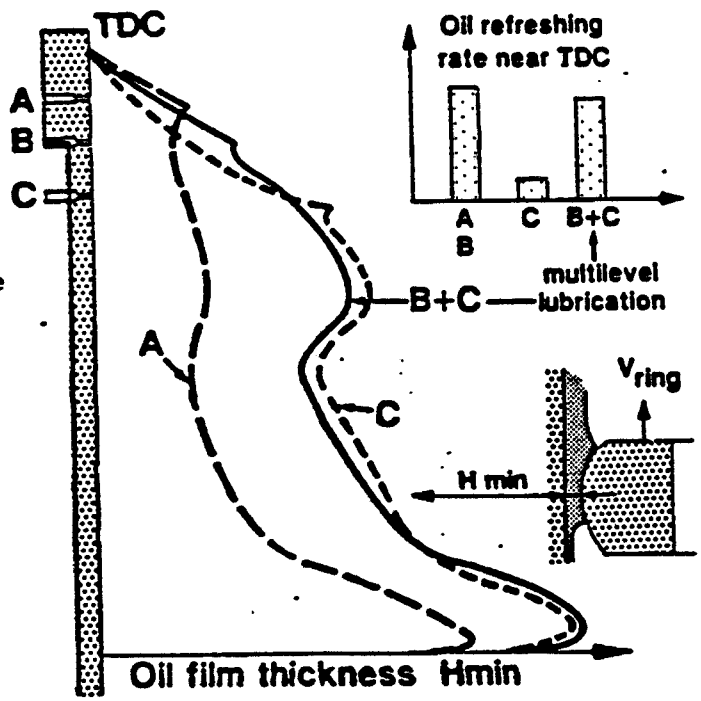


Fig. 5.6 The Sulzer RTA multilevel cylinder lubrication, and relative oil film thickness (courtesy of Sulzer Bros. Ltd.)

DIAGRAM FOR TIMING INJECTION OF CYL. OIL BY MECHATRONIC

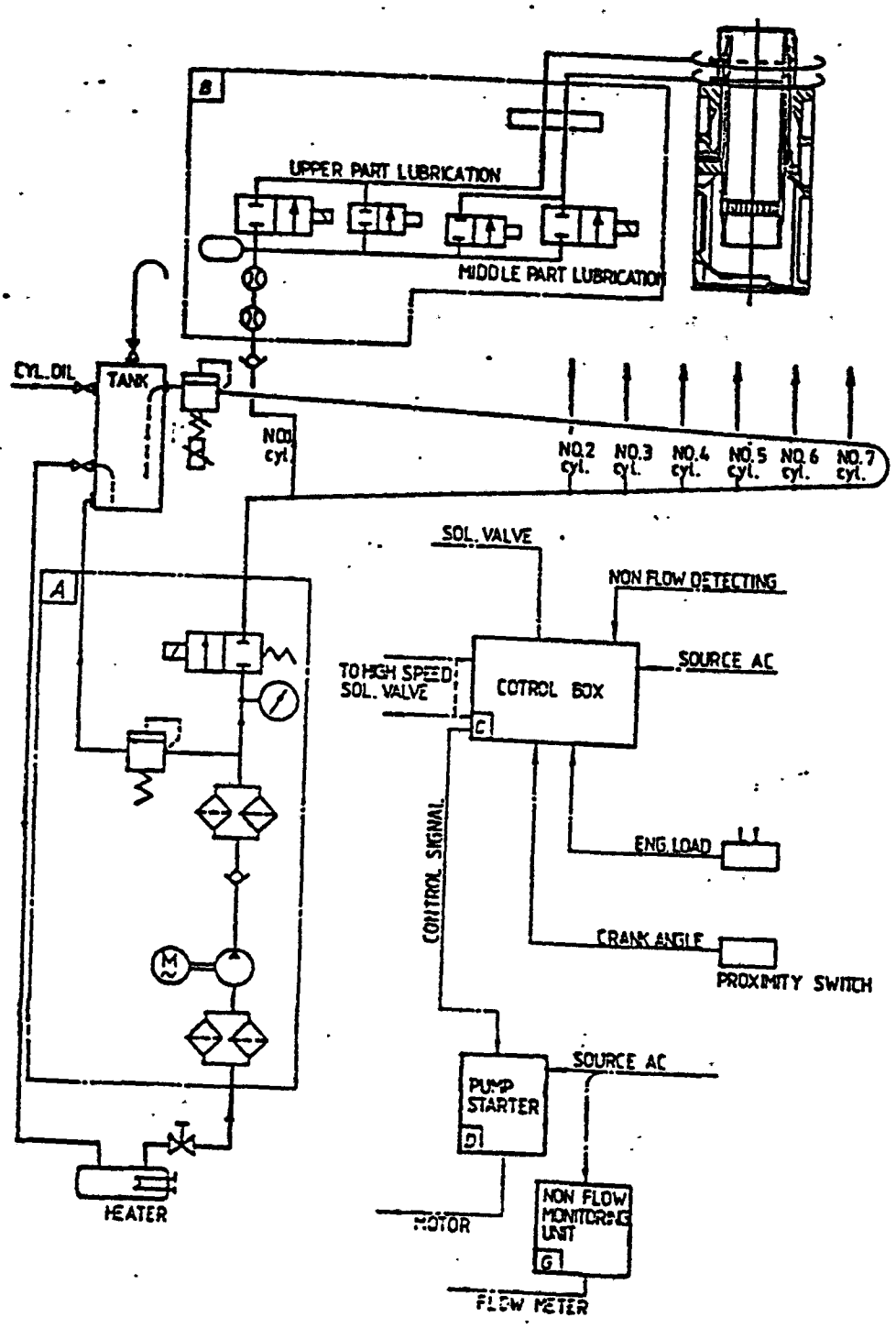
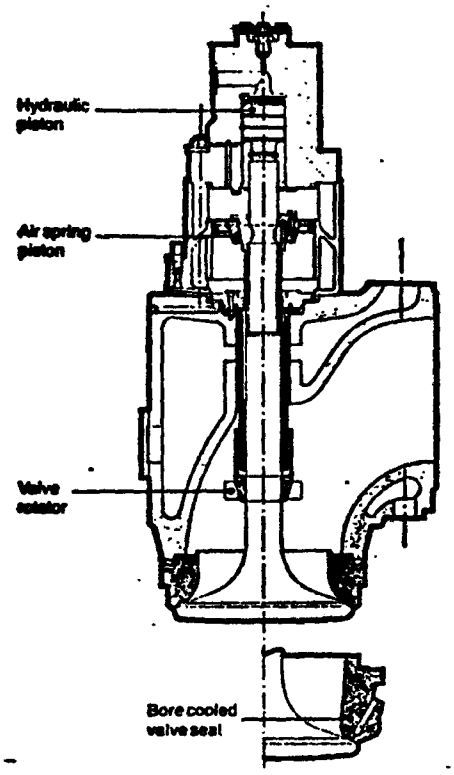
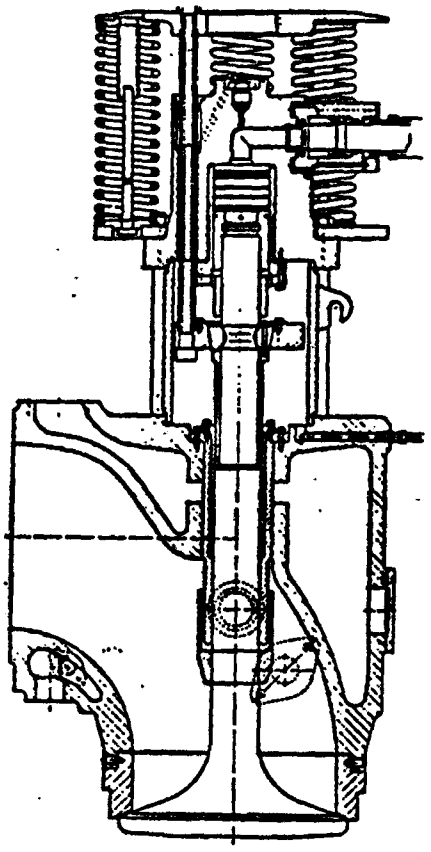


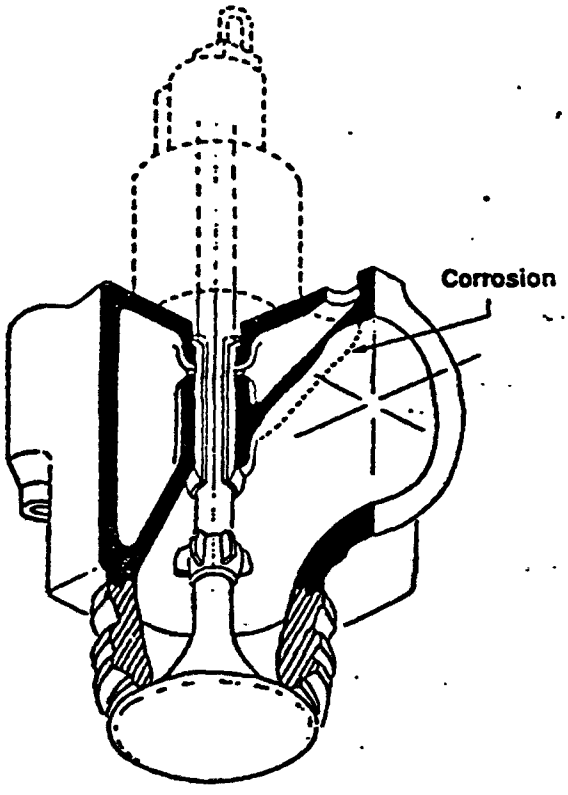
Fig. 5.7 Courtesy of Sulzer Bros. Ltd.



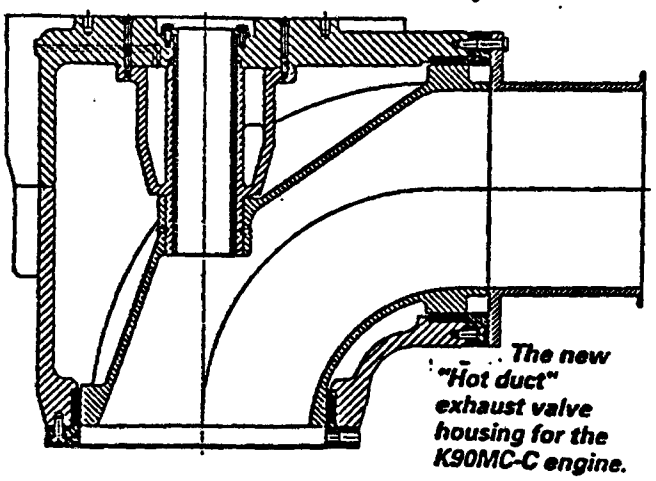
New exhaust valve with bore cooled valve seat



Elder generation exhaust valve with uncooled valve seat



Cold corrosion in exhaust valve housing



The new "Hot duct" exhaust valve housing for the K90MC-C engine.

Fig. 5.8 Courtesy of MAN-B&W.

CHAPTER VI

MEDIUM SPEED FOUR STROKE DIESEL ENGINE (MSE), CONDITION MONITORING AND EXHAUST EMISSIONS VERSUS THE USE OF HEAVY FUEL OILS

6.1.0 INTRODUCTION

The development of medium speed four stroke diesel engines (MSE) has progressed significantly during the decade of the eighties. MSE for main and auxiliary services are increasingly required to operate on the same poor quality fuels as slow speed engines. The unifuel marine power plant is almost a precondition for new installations.

The increasing complexity of power plants installations has heightened the need for adequate monitoring of these plants. The global awareness of the detrimental effects of engine exhaust emissions on the environment and living species has brought about regulations to minimize these effects.

Therefore, this chapter is divided into two parts. Part I will deal with medium speed four stroke diesel engine design and operational parameters with respect to the combustion of HFOs. These considerations will only deal with specific aspects where they are more intense, or where they differ from previous discussions of the slow speed two stroke diesel engine.

The effects of HFO qualities and the engine requirements from the storage, treatment/conditioning and booster systems as were discussed apply equally for MSEs. The inherent differences in the injection system, combustion chamber and lubricating systems of the MSE compared to the slow speed two stroke diesel engine will be discussed.

Part II will deal with condition monitoring of diesel engines for the efficient use of HFO. The necessary engine parameters which should be monitored as the basis for making decisions will be mentioned. The development of expert systems and their application to supplement the human element in condition monitoring will be discussed.

Exhaust emissions from plants burning fossil fuels are increasingly being scrutinized and regulated. Exhaust emissions from the combustion of HFOs in diesel engines are no exception. The various pollutants found in diesel engines exhaust gases will be discussed with respect to their origin, formation and effects.

Developments related to reducing the unwanted by-products found in exhaust gases from the combustion of HFO will be mentioned. Design and operational considerations as they affect the latter will be summarized.

PART I

6.2.0 THE MSEs INJECTION SYSTEMS

The injection systems for MSEs are subjected to severe dynamic loading due to the higher operating RPM of 300-1000. A higher temperature fluctuation is also prevalent

due to the higher thermal cycle as compared to the slow speed engine. The use of HFO in MSE has compounded these already extreme conditions and the reliability of the engine in general has been a focal point of development.

The fuel pumps and injectors are susceptible to similar detrimental effects of HFO as were discussed in Chapter V. The peculiar aspect of the injection system of MSE is the higher demand for proper atomization of HFO to reduce ignition delays. Inherently, HFOs have ignition delay qualities which can be measured as calculated carbon aromaticity index (CCAI). This fuel quality parameter will become increasingly demanding from the MSE operator. See fig. 6.1 for the relationship between fuel viscosity, density and CCAI as they affect combustion.

To minimize the effect of the poor ignition quality of HFOs, designers of MSEs increased the dynamic injection pressure of the fuel. The high-pressure injection system operates up to 1300 bars and more. This high energy injection ensures a faster admission and finer atomization of the delivered fuel. These aspects contribute substantially to shorter injection and combustion periods with a corresponding optimization of the heat release period.

The significant reduction in specific fuel consumption (SFOC) is partly attributed to the foregoing. Prolonged HFO operation at low loads without the unwanted prospect of incomplete combustion and its associated by-products is now possible. The application of VIT to MSE, coupled with the relatively higher injection pressures at varying loads are plausible developments with regards to MSE capabilities to burn HFOs.

The HFO injection system for MSE could be of several designs. These designs include the high pressure accumulator electronically controlled single injection system (1500 bars), the high pressure booster system (500 bars) to the injection pump for single injection or electronically controlled pre-injection single injector system (1200 bars). The high pressure twin injection system with a single injection pump for the pre-injector and main injector at pressures up to 2000 bars is also available. See fig. 6.2a and 6.2b.

The positive and negative aspects of these various injection systems are centered primarily around their power requirements, maintainability and reliability. The desired effects for the efficient combustion of HFOs and the reduction of the steep pressure gradient associated with ignition delays can be achieved by any of these systems.

The operator has to be confident that the operating instructions as provided by the engine manufacturer, particularly when VIT is incorporated, are clearly understood and strictly adhered to. The recommended grades of fuels and the test results of fuels delivered should be compared in full detail. The importance of adequate fuel treatment is also a predominant consideration with regards to MSEs.

6.3.0 THE MSE COMBUSTION CHAMBER FOR HFO

The combustion chamber design for HFO operation had to provide for a comparatively larger cylinder clearance volume. This larger clearance volume facilitates the

proper penetration of high asphaltene fuel throughout the combustion chamber. A more even distribution of the combustion process occurs in the chamber.

Concurrently, the injection system had to be matched to the combustion chamber geometry, particularly the piston crown. This process enhanced the distribution of the fuel droplets and minimized fuel impingement on combustion chamber members. The optimum desired heat release pattern over varying loads was also determined as a function of the injection pressure, nozzle holes configuration and piston crown geometry. See fig. 6.3.

The use of the more efficient constant pressure turbocharger and the scoop design of the cylinder head air intake port periphery are also contributory factors to the efficient combustion of HFO. The higher charge air pressure assures that enough air is available for combustion over varying loads. The scoop design coupled with the high charge air pressure assure that the combustion chamber is swept clean of exhaust gases and that a turbulent mixture of the fuel and air occurs.

The stroke to bore ratio, compression pressure, engine revolutions and charge air temperature were factors which were manipulated by designers to improve MSE's capability to burn HFOs. Some designers maintained the traditional 1.1/1 stroke/bore ratio and the lower compression pressure. They opted instead for increasing the charge air temperature relative to the engine load. Other designers opted for a longer stroke with a stroke to bore ratio of 1.4/1 and a higher compression pressure.

The latter design considerations resulted in lower engine revolutions and a relative increase in the time available for combustion. The increased compression pressure of up to 110-130 bars meant higher air temperature at the end of compression for the speedy ignition of the fuel.

The above two developments primarily improved MSEs combustion efficiency of HFOs over varying load. Secondly, an expanded range of HFO up to 700 cSt at 50°C can be used in these engines. All of the developments discussed in this section contributed substantially to the reduction in MSEs SFOC as well.

6.3.1 MSE CYLINDER LINERS, CYLINDER HEADS AND EXHAUST VALVES

Traditionally, MSEs cylinder liners and heads have enjoyed relatively lower temperatures as a result of the additional (intake) stroke. Unfortunately, this is an unwanted feature with regards to the combustion of HFOs and low temperature corrosion. See **fig. 6.4a** for contemporary MSE combustion chamber components temperatures. The conventional cast iron liner is highly susceptible to wear when operating on HFO irrespective of the dynamic lubricating feature associated with the higher mean piston speed.

To alleviate these difficulties, the bore cooling of these components was introduced. The proximity of the cooling water to the working surface of the component is predetermined to maintain the desired temperature. Intensive cooling by the use of the "jet cooled" principle in the cylinder liners further guaranteed the equalization

of the temperature along the periphery of the liner. Some designers still apply the insulating tube insert concept as was used in some slow speed engine liners. See fig. 6.4b for a bore-jet cooled liner.

The bore cooling concept was extended to the cylinder heads and a better temperature control of the exhaust valve and nozzle tip is now feasible.

Traditionally, MSE cylinder liners operating on MDO enjoyed a lower cylinder liner wear rate than the slow speed engines. However, with the use of HFO in MSEs, this positive aspect has diminished due to the abrasive constituents and the eutectic complexes associated with the combustion of HFO. The use of laser hardened liners, nodular graphite cast iron liners and other forms of surface treatment as was mentioned in Chapter V-5.3.0 have now contributed to reduced liners wear in MSEs. Forced cylinder liner lubrication in addition to the splash and mist method has also contributed to the respectable MSE liner wear rate of 0.02mm/1000hrs and lower.

The exhaust vales for the high temperature MSE have been a crucial aspect with regards to the combustion of HFO, the mean time between overhauls (MTBO) and the durability of the valve. To minimize the prospect of high temperature corrosion, cooled valve seats were introduced. Improved mechanical valve rotators for both exhaust and intake valves, or the exhaust gas driven impeller mounted on the exhaust valve have all ensured against localized overheating of sealing surfaces.

The materials now used for exhaust valves are high-quality nimonic valves or stellite coated sealing surfaces. The nimonic valves have given a reliable performance and an increased MTBO of 10,000 hours and more. In some cases the sealing surfaces do not require grinding and lapping after a prolonged period of operation on HFO.

The prospect of low temperature corrosion has virtually been eliminated in the exhaust valve cage, cylinder head and liners. The improved cooling methods as were discussed and the relatively higher coolant temperature as recommended will guard against this. Again the role of the operator with regards to the operating temperatures can not be over emphasized.

6.3.2 MSE PISTONS AND PISTON RINGS

The MSE piston is increasingly being built in two parts. There are several considerations for this trend. Prominent among them is the need to provide a rigid piston crown with excellent thermal conductivity and high resistance to HFO related corrosion and wear. Concurrently, the piston skirt can be of lighter materials to reduce the magnitude of the reciprocating mass.

Alloy steel and nodular cast iron crowns with bore cooling arrangements are now used extensively. These two aspects of the design are essential in eliminating hot temperature corrosion and thermal deformation of the piston crown. The oil cooled crown is more adept in providing undistorted piston ring groves. Thus, blow-by and contamination of the crankcase by the by-products of combustion are minimized.

The piston ring groves are specially treated with electro-hard chromium plating. The top ring face is plasma coated while the remaining ring sealing surfaces as well as the other rings are chromium plated. See fig. 6.5. These combinations have contributed to piston ring grove and ring wear rates of 0.01 and 0.02mm/1000hrs respectively. These hardened surfaces of the piston rings and liners have little embeddability characteristics. Therefore abrasive contaminant is a very sensitive parameter for MSE.

6.4.0 THE DUAL-PURPOSE LUBRICANT FOR HFO OPERATION

The system oil for lubricating MSE running gears must be capable of reducing deposit formation in the piston ring zone and neutralizing the corrosive acids formed from the combustion of HFO. The dual-purpose characteristics of the lube oil must have excellent load carrying capabilities and thermal stability. The cooling of the piston crown by the system oil is also an important consideration when selecting the lubricant.

The current grades of lube oil used in MSEs have viscosities of 9.3-12.5 cSt at 100°C for SAE 30 and 12.5-16.3 cSt for SAE 40. The SAE 40 lube oil on the lower end of its viscosity range is preferred for dual-purpose. However, some manufacturers recommend SAE 30 for the system oil and SAE 40 for the cylinder liners when fitted with forced-lubricators.

MSE system oil must be closely monitored and supplemented regularly to assure that the right alkalinity is maintained. Fig. 6.6 underscores the need for regular

analysis of the system oil irrespective of the oil consumption rate and fuel sulphur content. To neglect this operational necessity would amount to an open invitation for acid corrosion of the bearings and increased deposits formation in the piston groves.

The system oil is easily contaminated by the by-products from the combustion of HFO due to the unseparated combustion space and crankcase. Regular and in some cases continuous purification of the system oil is mandatory.

PART II

6.5.0 CONDITION MONITORING OF THE USE OF HFO IN DIESEL ENGINES

Condition monitoring of the operational state of diesel engine plants is a necessary activity which must be implemented to the highest degree of professionalism. This is not a new idea as operators have traditionally used the human element and the limited instrumentation provided to effect this idea.

Today there are expert systems available to assist and augment the human element in this field. The widespread use of microprocessors and electronic sensors have made on line diagnosis of the engine internal parameters possible.

It is expedient to extract the most out of expert systems and to include the fuel monitoring aspect as well. This necessity can be underscored by the following factors:

1. The decrease in available man power to effectively implement the human element of condition monitoring;

2. High initial investment in the diesel engine plant;
3. Increasing complexity of diesel engines external adjustable parameters;
4. Increased demand for longer running periods between overhaul;
5. Decreasing HFO qualities and diverse sources of HFO supply;
6. Increased HFO induced problems with respect to the operation of the engines, the durability of their components and the reliability of the engines.

6.5.1 MONITORING HFOs USE IN SLOW SPEED TWO STROKE DIESEL ENGINES

The slow speed injection system can be easily monitored by direct electronic sensors. The opening pressure, the time and duration of the injector needle lift, the opening characteristic of the injector can all be measured and compared with the ideal. Concurrently, from the same sensor, the injection pump dynamic injection pressure and the pump's valve operating characteristics can be determined.

The relevant cylinder indicator diagram can be taken electronically or mechanically. The cylinder and piston ring wear rates as well as the relative surface temperatures of stationary combustion chamber members can be measured.

With these measured data of the engine internal parameters and supported by the available data of the external parameters, excellent decisions can be made. These decisions will promote the efficient combustion of HFO,

minimize the associated detrimental effects and by-products as well as optimize the engine performance.

6.5.2 MONITORING HFOs USE IN MEDIUM SPEED FOUR STROKE DIESEL ENGINES

The medium speed engine components are comparatively smaller and disproportionately affected by HFO qualities than those of slow speed engines. Primarily, HFO with a poor ignition quality could cause a disastrous pressure gradient of 50 bars/°CA or more in MSEs. MSEs develop very high inertia forces which are a function of the square of the RPM (angular velocity). Microseizures occurring in the combustion chamber as a result of abrasive contaminants from HFOs could be catastrophic. These considerations underscore the need for adequate condition monitoring of MSEs.

Condition monitoring of the injection system as was suggested for slow speed engines is not easily practicable for all sizes of MSE. Nevertheless, they should be used where feasible. Monitoring of the combustion/compression pressures along with full pressure-volume diagrams will give adequate data. The cylinder liner and piston ring wear rates are highly recommended to detect the onset of seizures.

The system lube oil is a valuable asset in determining the effectiveness and consequences of burning HFOs. In addition to monitoring the lube TBN, the insoluble contents of the lube oil will reveal the extent of incomplete combustion. Advance methods employing spectrography, ferrography and magnetic plug analysis will give good indication of the source of metal contaminants.

Condition monitoring of HFO related abnormalities is extensive. What ever the method or system employed, the diagnosis and remedies should not be considered cosmetic by the operator.

6.6.0 DIESEL ENGINE EXHAUST EMISSIONS FROM THE COMBUSTION OF HFO

The process of combustion produces by-products with varying compositions. These compositions reflect the molecular makeup of the combustible material and the products of the chemical reaction of the combustion process itself. The combustion of HFOs produces nitrogen oxides (NO_x), sulphur oxides (SO_x), carbon monoxide (CO), hydrocarbons and particulates.

These by-products of combustion are detrimental to the environment and living species. The two by-products of immediate concern are NO_x and SO_x. Smog, emphysema and acid rain are associated with NO_x, while SO_x is primarily responsible for acid rain. Smoke is the result of poor and incomplete combustion. Smoke is a mixture of particulates and hydrocarbons which are considered to be carcinogenic.

Against this background, many industrialized countries have issued regulations to limit the concentration of these pollutants. Particulates and hydrocarbon concentrations can be limited by the smoke limit which in any case is achievable from good combustion. Carbon monoxide concentration in diesel engine exhaust is a minimum compared with automobiles and poses no real threat. Sulphur oxides can be limited by the sulphur

content of the fuel. In this case the burden for the removal of sulphur will be placed on the producers of HFOs.

This leaves nitrogen oxides as the prime pollutants which must be dealt with from the design and operational perspectives of diesel engines. The formation of NO_x is due in part (less than 30%) to the HFO chemical composition of nitrogen compounds. The remaining 70% is formed from the chemical reaction of free oxygen and nitrogen atoms at peak temperatures during combustion. The residence time of these atoms at peak temperatures also enhances the formation of NO_x.

To approach the reduction of NO_x from the engine design perspective entails the manipulation of several variables. These variables are numerous with varying combinations and complexities. The desired result for a respectable reduction in NO_x and other pollutants would be to have a short isobaric combustion process in the diesel engine. Unfortunately this is still not in reach.

Conditioning of the fuel by emulsification with water has proven that NO_x emission can be reduced by 30%. This partial reduction is not enough to meet the required limit. A 10% water content could achieve the 30% NO_x reduction without a noticeable decrease in the engine maximum combustion pressure. To introduce up to 30% water content in the fuel would lead to a reduction in peak temperatures and maximum combustion pressures. This method is counter productive for the newer engines with the maximum combustion pressures as a major parameter for their performance.

The external control of NO_x by 'Selective Catalytic Reduction (SCR)' seems to be an effective method for controlling NO_x emission. The SCR system introduces a predetermined amount of ammonia based on engine load into the exhaust gas. This mixture goes through the catalyst reactor where most common forms of NO_x are converted to nitrogen and water vapor. See fig. 6.7 for a schematic layout of an SCR system for a slow speed diesel engine.

However, the ammonia based SCR system poses great threat to personnel onboard. A harmless mixture of urea and water has been developed by HUG Engineering AG of Switzerland and adopted by ABB Flakt Marine of Sweden to replace ammonia. This method of reducing NO_x is called "NIXHAUST™". NIXHAUST™ combines the SCR and oxidation process to convert NO_x to pure nitrogen and water vapor. Hydrocarbons and carbon monoxide are also converted to water and carbon dioxide. The oxidation of additional SO_x in the exhaust uptake can be controlled by the use of particulate filters (Orjan A. Gatmalm 15).

This system certainly seems to be well adopted for controlling the detrimental emissions from the combustion of fossil fuel and HFO in particular. The extensive use of this system will be governed by the regulations as adopted by the major maritime nations.

ANNEX—E

Fig. 6.1 Fuel viscosity, density and CCAI relationship as they affect combustion

Fig. 6.2a High-energy constant pressure accumulator injection system

Fig. 6.2b High-energy pre-injection system

Fig. 6.3 Matching of combustion chamber shape with injection system

Fig. 6.4a MSE optimum surface temperature to avoid high or low temperature corrosion

Fig. 6.4b Bore-Jet Cooled cylinder liner for optimum liner temperature control

Fig. 6.5a Piston ring lands electro-hard plating

Fig. 6.5b Piston rings plasma and chromium plating

Fig. 6.6 The influence of crankcase oil alkalinity on piston deposits and the change of TBN with service time under differing conditions.

Fig. 6.7 Selective Catalytic Reduction schematic layout for a slow speed diesel engine

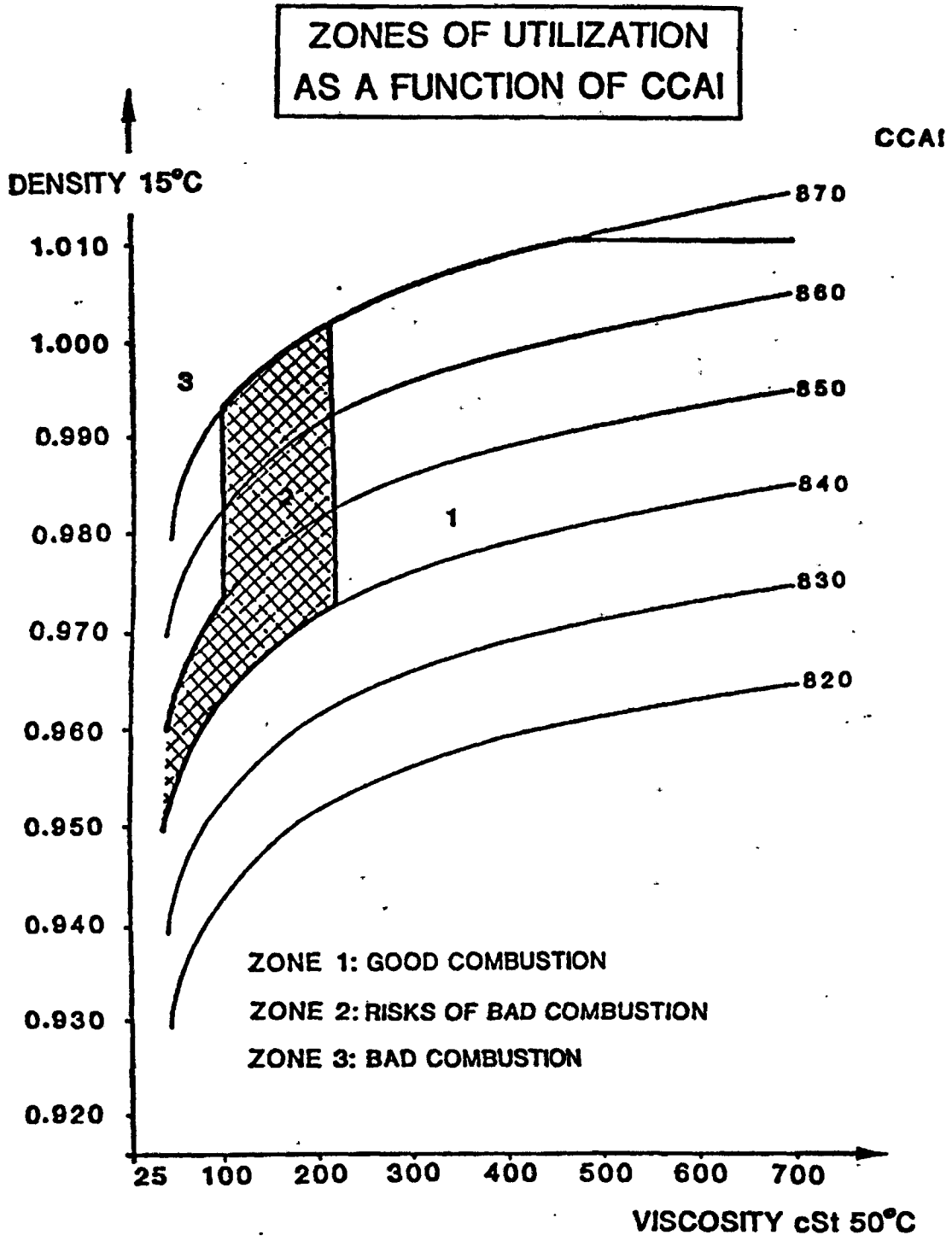


Fig. 6.1 Fuel viscosity, density and CCAI relationship as they affect combustion (courtesy of S.E.M.T. Pielstick).

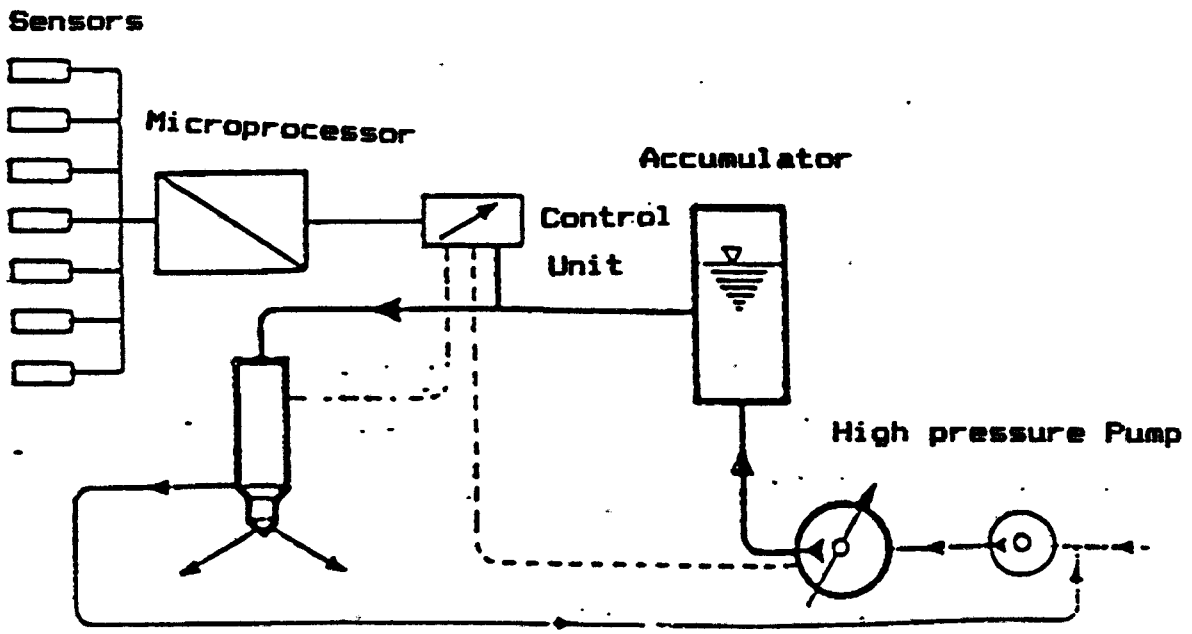


Fig. 6.2a High-energy constant pressure accumulator injection system

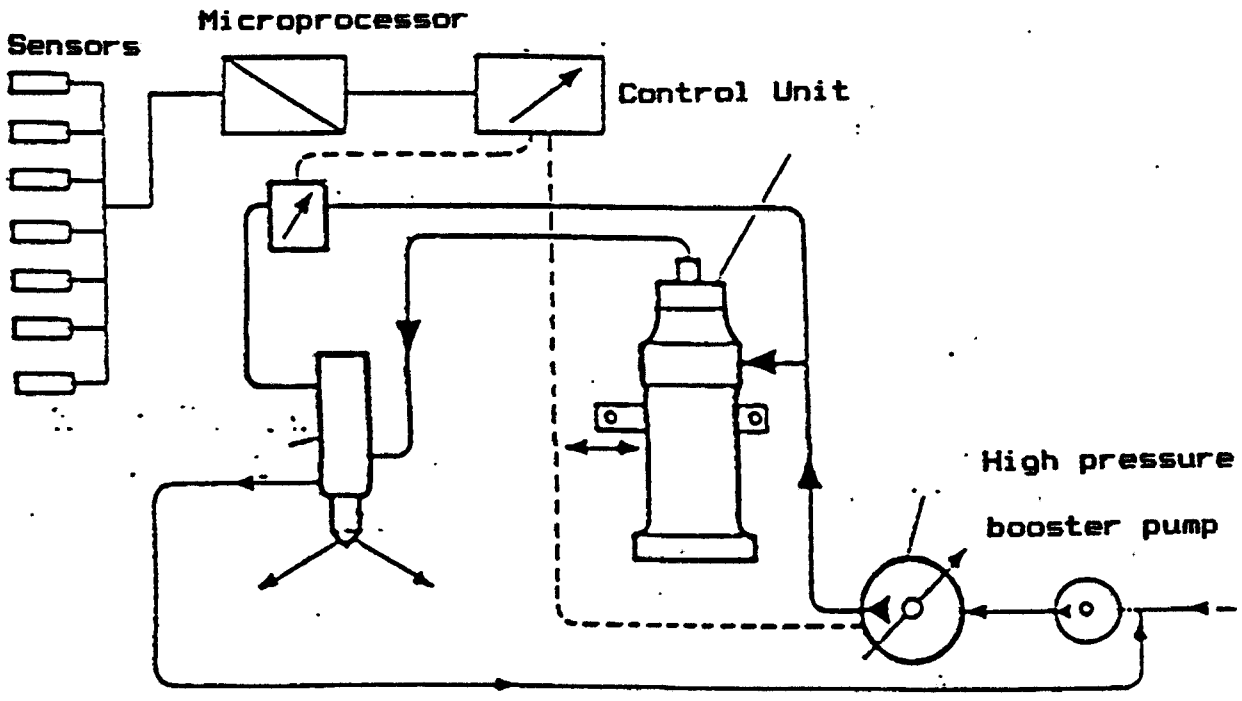


Fig. 6.2b High-energy pre-injection system

An example of the way in which combustion chamber shape and injection system are effectively matched

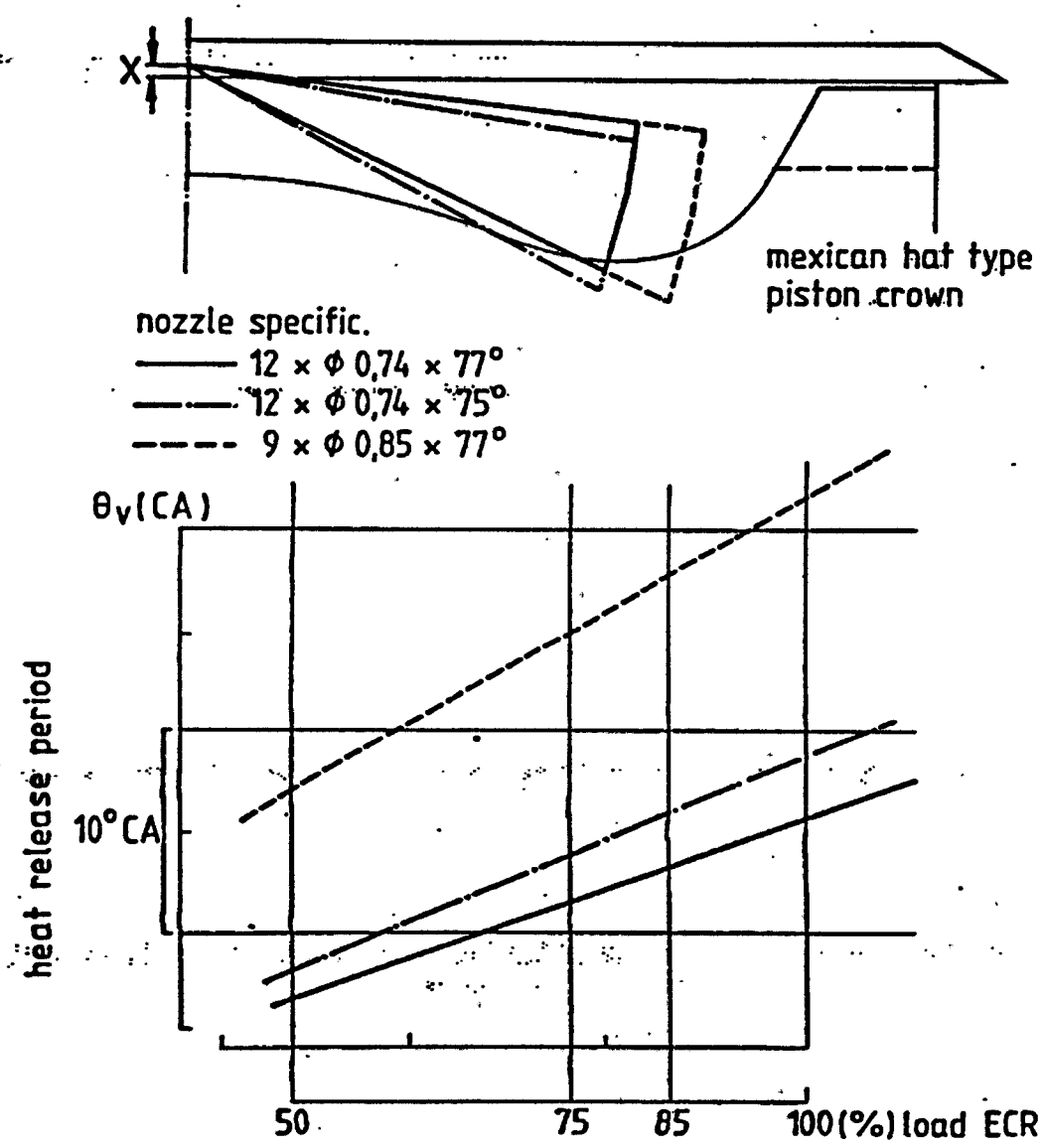


Fig. 6.3 Courtesy of Sulzer

ZA 40

Measured temperatures in °C in combustion chamber area

660 kW/cyl. at 600 r.p.m. - b.m.e.p. = 21.9 bar

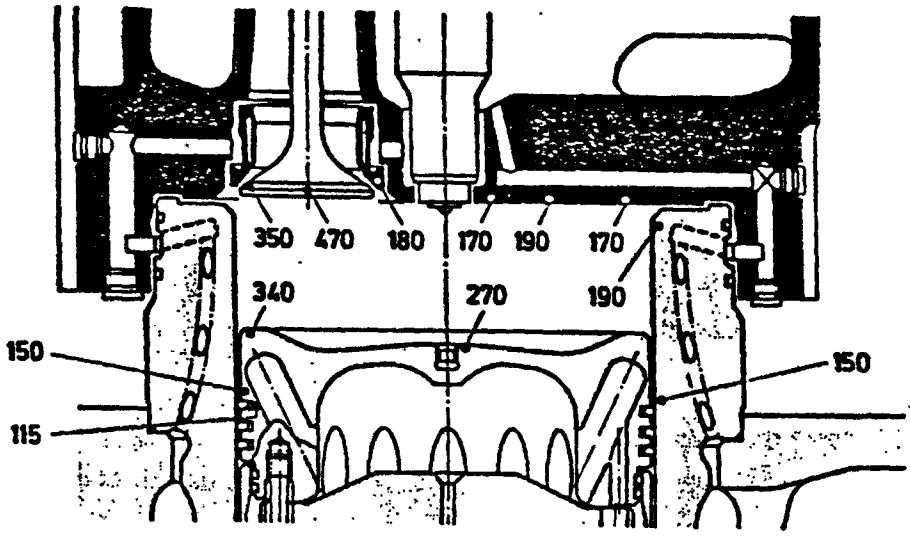


Fig. 6.4a MSE optimum surface temperature to avoid high or low temperature corrosion (courtesy of Sulzer).

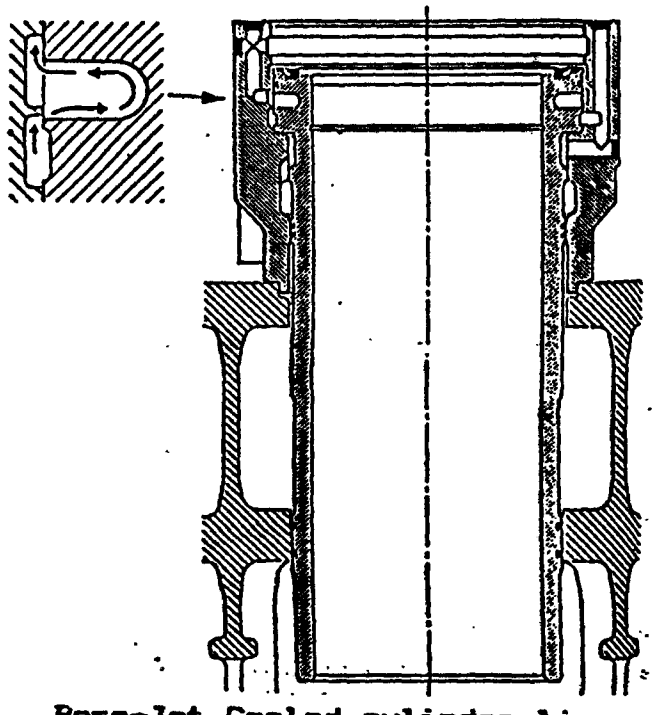
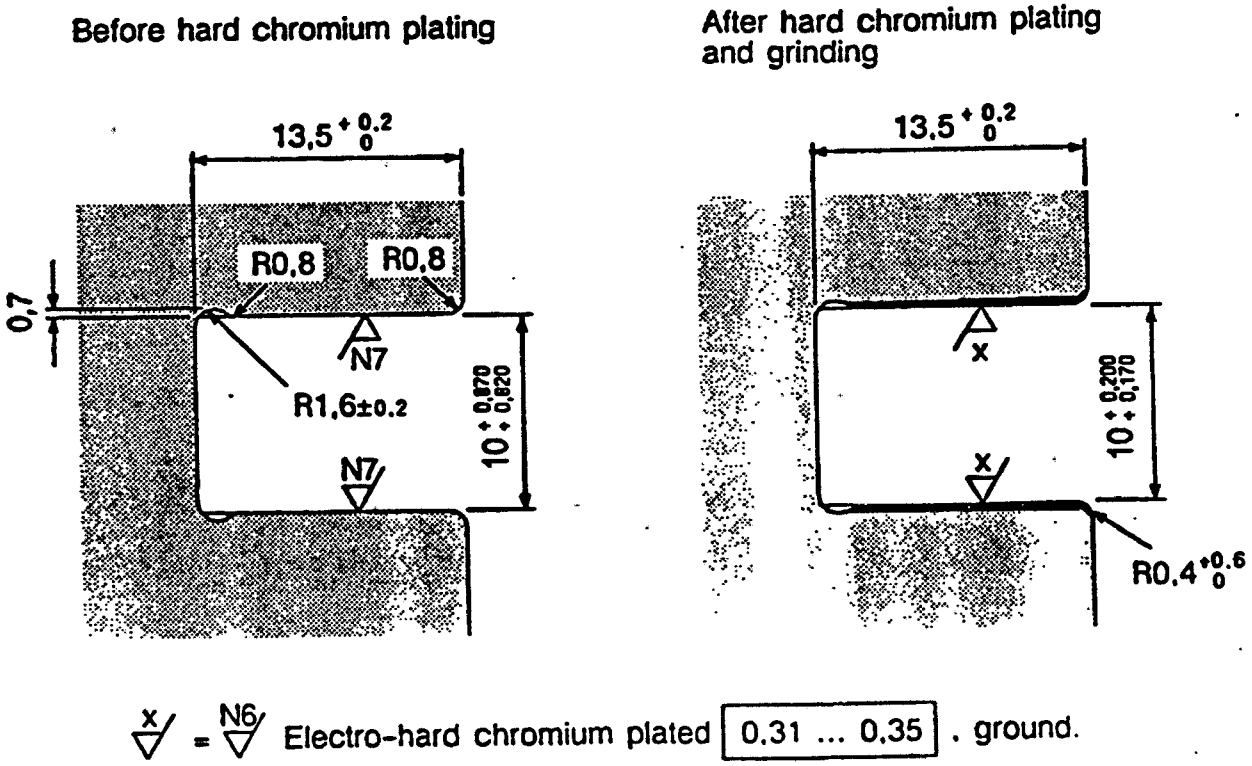


Fig. 6.4b Bore-Jet Cooled cylinder liner for optimum liner temperature control (courtesy of MAN-B&W).



x = N6 Electro-hard chromium plated 0.31 ... 0.35 , ground.

Fig. 6.5a Piston ring lands electro-hard plating

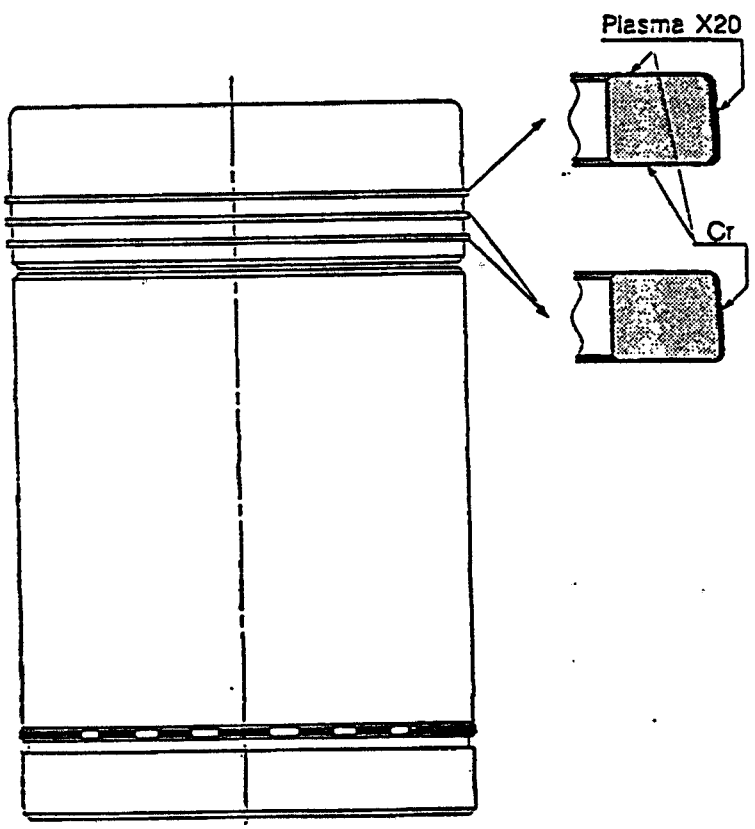
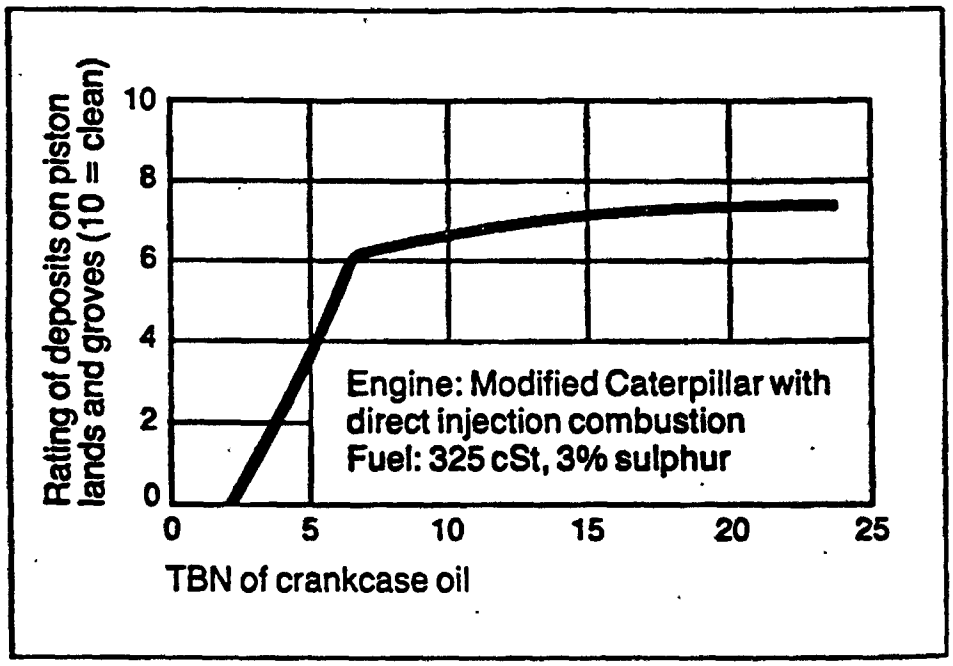
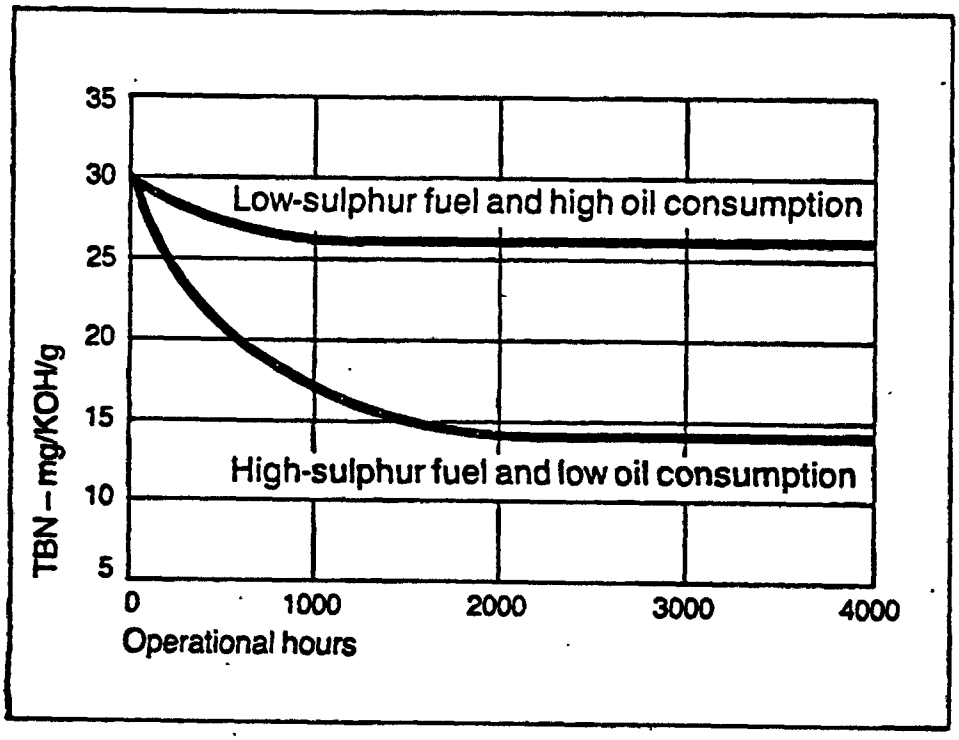


Fig. 6.5b Piston rings plasma and chromium plating

(Courtesy of Sulzer)



Influence of crankcase oil alkalinity on piston deposits.



Change of TBN with service time under differing conditions.

Fig. 6.6 Source: Shell Marine. Lubricants and Fuels in Ships. pg. 58.

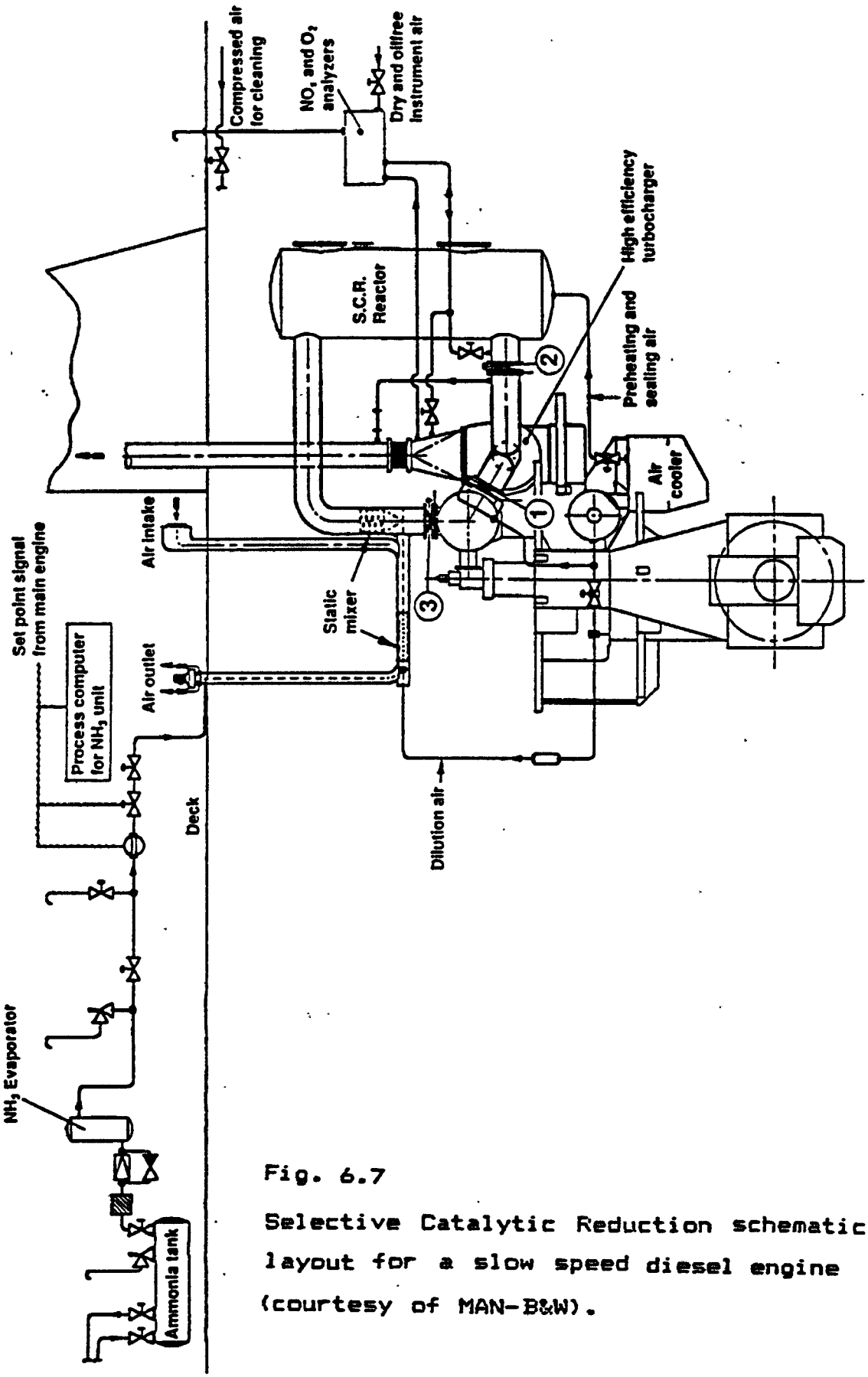


Fig. 6.7

Selective Catalytic Reduction schematic layout for a slow speed diesel engine (courtesy of MAN-B&W).

CHAPTER VII

MANAGING THE USE OF HEAVY FUEL OILS IN DIESEL ENGINE PLANTS

7.1.0 INTRODUCTION

Operators of diesel engine plants, particularly marine diesel engine plants are involved in the management of a complex and dynamic process. Their methods of achieving the desired results are viewed from a technical perspective rather than a combination of technical and management skills.

For most of these operators, their formal training did not expose them to management techniques. The few that were opportune to obtain these techniques have not been able to correlate them to the work environment. Secondly, they usually forget the benefits of using these techniques when they aspire to higher levels of responsibilities within the plant.

Therefore, this chapter will discuss basic management principles aimed at providing a working knowledge for operators. The classical approach to management will be the focal point for developing a practical working sequence for the efficient use of HFOs.

The functions of management will be discussed relative to the dynamic process of HFO use throughout the system. The

flow of HFO through the plant will be categorized and a systematic approach will be developed to assure the best possible result. The process to be managed will henceforth be called "The HFO System" (HFO-SYS).

7.2.0 MANAGEMENT CONCEPTS

Management is a process which could be a simple and a non-scientific approach an individual uses to obtain personal results. Management on the other hand could be a complex process involving the use of scientific methods. Nevertheless, these two extremes apply the same basic underlying concepts. James H. Donnelly, Jr., et all suggested that "management is the process undertaken by one or more individuals to coordinate the activities of others to achieve results not achievable by one individual acting alone" (5).

The diesel power plant involves more than one individual with the single goal of producing a reliable, cost effective, sustainable and efficient power supply. The HFO system is a part of this complete process. A further breakdown reveals that the HFO-SYS in itself is a dynamic whole which requires management concepts to integrate it into the complete process. Thus, the four classical functions of management which include planning, organizing, directing and controlling should be understood and used by the operator.

The planning function in the HFO-SYS is for the short-term. Each time HFO is to be purchased this function of management must be exercised. The objective in every case is well defined as 'the efficient use of HFO in the diesel engine power plant'.

The planning function in the HFO-SYS involves the purchasing aspect being correlated with the storage and usability factors as the first phase. For the marine power plant, this phase involves the ship-to-shore interface where the management tool of effective communication is essential.

The second phase of the planning function is exercised within the plant. The operators should apply a systematic process whereby the qualities of the HFO purchased are matched with the various subsystems and components of the HFO-SYS to determine possible points of difficulties. Based on this determination, the HFO-SYS disposition matrix can be established to highlight these difficulties.

The organizing function in the HFO-SYS begins with implementing the plans developed from the first phase of planning. To adequately and expediently receive, distribute and store HFO, an excellent organization is necessary. The personnel involve in this activity could easily follow a standardized organizational chart. The various activities to be carried out should be clearly spelled out. The delegation of responsibilities and authority should be commensurate with the level of experience and knowledge of the process.

The organizing of the plant's personnel has traditionally been based on the level of experience, grade of license and a one way downwards flow of information. This is all good and well to maintain the authority of the senior personnel. However, this organizational arrangement is strategically geared towards evaluating the performance of personnel which in itself is counter-productive for the

HFO-SYS. There is often a lack of confidence amongst personnel. This often leads to frequent independent corrective actions by personnel to remedy mishaps irrespective of its expediency.

The organizing of the HFO-SYS should first eliminate the filtering of information among personnel and promote the free exchange of information and knowledge. Inter-personnel confidence should be fostered. Frequent negative remarks about personnel performance should be discouraged as the reverberations from this could demoralize them.

The directing of the HFO-SYS activities falls under the umbrella of the head of the plant. For the marine power plant the Chief Engineer is responsible. In order for the plans to be implemented according to the organizational layout, the head of the plant must be motivated and exhibit excellent leadership qualities. Absolute control of the process without demeaning those responsible for the various subsystems is a must. One important asset which ensures the effectiveness of this function is the expeditious transfer of knowledge to the least knowledgeable.

The controlling aspect of HFO-SYS should embrace test results and condition monitoring. Negative questions to junior personnel should be avoided. The points at which controls are exercised should be known and the reasons for establishing them should be clear. Effective control of this dynamic process is essential and feedback to the directional head is important.

With these basic management functions in place and understood, a systematic approach to the management of the HFO-SYS would provide the background for unequivocal decision making. This approach recognizes the inter-relationship of subsystems and systems as part of a dynamic whole. The performance of this dynamic whole is only possible with good management.

7.3.0 MANAGEMENT MODELS FOR THE HFO-SYS

The planning, organizing, directing and controlling models (PODC) for the HFO-SYS are diagrammatic layout of activities related to the specification of HFO to be purchased, the storage and transfer of HFO, the treatment/ conditioning of HFO and the engine and exhaust gas user equipment parameters relative to the qualities of HFOs.

The PODC models are divided in alphabetical order to form subsystems and sequential phases. These models are theoretically connected to each other to form a closed loop. The various aspects which should be planned, organized, directed and controlled with respect to the HFO-SYS are numbered in numerical order for identification with the subsystems and the sequence of events. At the end of some numbered items is a parenthetical citation of references to the applicable parts of this dissertation (section number).

7.4.0 PODC MODEL FOR THE PURCHASE OF HFO

MODEL-A: The Specification of HFO is a suggested routine to establish the maximum and minimum fuel specifications for the diesel engine plant. This process can be

standardized and the result compared with known HFO specifications to determine the acceptable grades of HFOs.

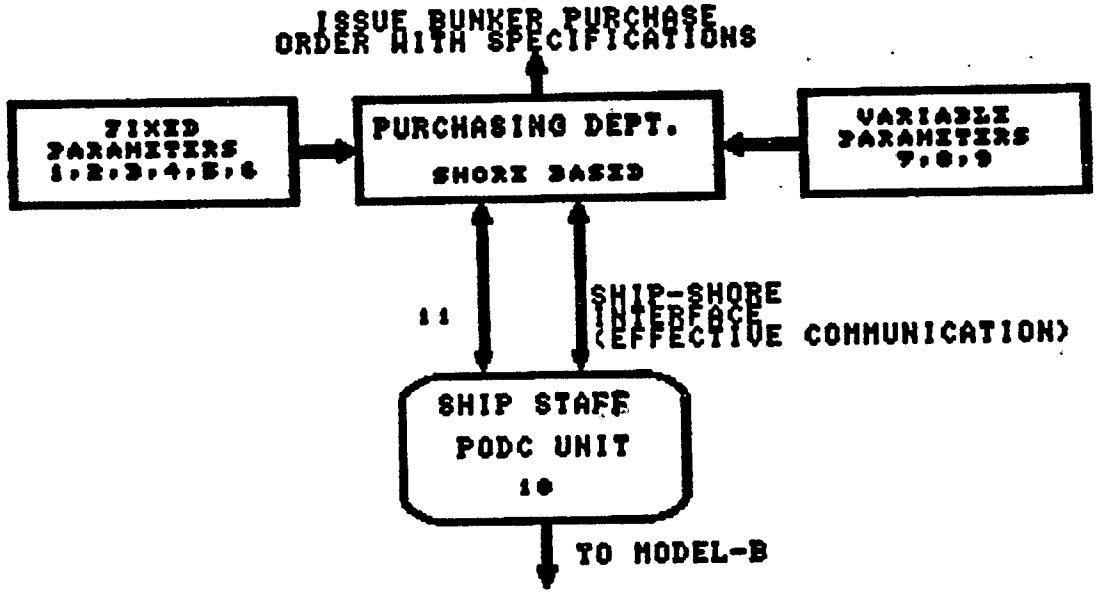
This model deals exclusively with activities related to the HFO-SYS. The actual PODC functions for the purchasing of HFO as carried out by the shore based purchasing department will include other factors which are not relevant to the HFO-SYS.

Economic considerations, particularly discount purchasing of HFO should not be the prime determining factor when purchasing HFO. Some companies prefer to use the lowest quality and cheapest grade of available HFO. The economics of this policy should be supported by a cost/ benefit analysis with a better quality and a higher priced HFO. This analysis should consider the net calorific values of the HFOs, the cost of heating during storage and for injection. The latter is particularly important if the auxiliary boiler is to be fired to supplement the heating demand.

The result from this analysis should be sufficient to deter any premature decision based solely on the price of HFOs. The maintenance cost/activities should be quantified over a period of time to further support this decision making process.

The HFO quality parameters which can be established from MODEL-A are: viscosity, density, sulphur content, and pour point. Other fuel quality parameters can also be established from the engines manufacturers recommendations. The request to the tender for HFO should always have the fuel quality specifications.

MODEL-A THE SPECIFICATION OF HFO



FIXED PARAMETERS

1. The capacity of the vessel's fuel storage tanks;
2. The number of fuel storage tanks for the separation of fuel to avoid incompatibility and the heating capacity of the storage tanks (3.2.0);
3. Engine manufacturers fuel specifications;
4. Centrifuge manufacturer fuel quality limitations;
5. The heating capacity of the line heaters for obtaining the injection viscosity (4.2.5);
6. The type of cylinder lube oil onboard (5.3.2, 6.4.0).

VARIABLE PARAMETERS

7. Applicable national regulations on the emission of SO_x versus ports of call;

8. The vessel trading route with respect to seasonal temperatures, availability and reliability of HFO supplies and duration of voyage;
9. The stability of the bunker market with respect to the price and quality of the fuel.

SHIP STAFF INPUT

10. Confirmation of available storage capacity including the ability to shift onboard fuel to create empty space.

CONTROL FUNCTION

11. The purchasing department should send to the ship a copy of the fuel purchase order with the fuel specifications. This should be accompanied by instructions to reject the fuel delivery if the bunker delivery note reveals any deviation in the allowable tolerance of the specifications.

7.5.0 PODC MODEL FOR BUNKERING OPERATIONS

Planning the bunkering operations is the first function of the shipboard staff in the HFO-SYS. The development of a proper plan would go a long way in promoting the efficient use of HFO. Very often the crew are very familiar with the bunkering operations including the system layout. This familiarity usually causes them to omit the planning aspect of this operation. When this omission occurs, small but crucial details which are not readily visible may be forgotten. This could lead to pollution, loss of fuel and contamination of different grades of fuels.

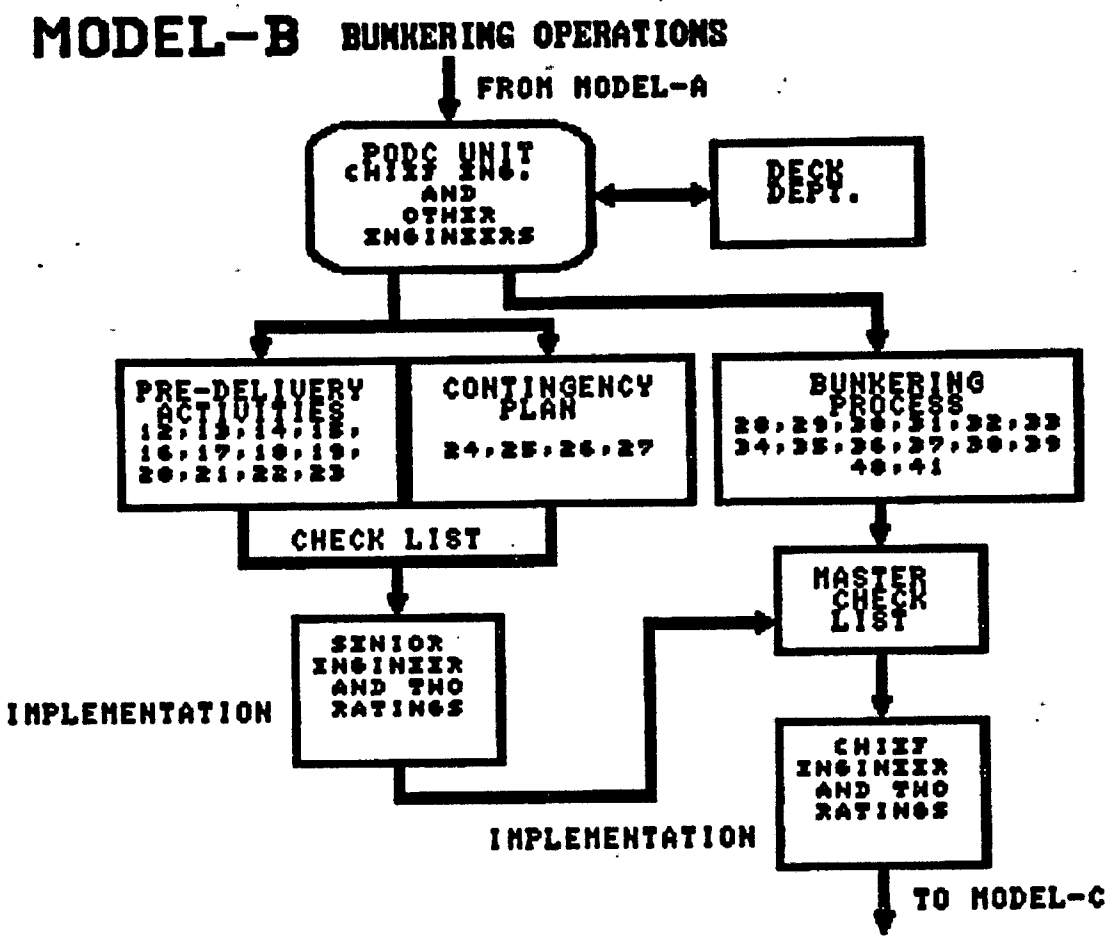
The PODC unit on board is headed by the Chief Engineer with the other engineers as members of this unit. The

deck department is consulted as may be necessary. The composition of this unit forms the permanent organizational arrangement for the HFO-SYS. The head may delegate responsibilities to members of this unit for implementing and controlling the plans developed for the various subsystems.

The Chief Engineer should maintain the directional authority for the HFO-SYS. MODEL-B PODC for Bunkering Operations examines the various aspects involved in bunkering operations. The pre-delivery activities and contingency plans can be executed by the senior engineer officer and two ratings with the aid of a check list as developed from the plans.

These two ratings must be part of the team for the entire bunkering operations. They should work in shifts if the duration of the operations is long, or in tandem if the operation is short and complex.

The Chief Engineer should exercise control of the former activities by reviewing the returned check list and spot check of strategic aspects. The Chief Engineer should take full responsibility for implementing the bunkering operations and he should not hesitate to summon additional personnel as needed.



PRE-DELIVERY ACTIVITIES

12. Confirm available storage space and quantity of fuel onboard. Shift fuel to create space as per confirmation to purchasing department. Confirm the accuracy of measuring equipment (automatic and manual tank gauging equipment).
13. Develop distribution plan for the quantity and grades of fuel to be received. Avoid or minimize mixing of incoming HFO with onboard HFO where possible.

Liaise with deck department to confirm stability and trim as per distribution plan.

14. Establish loading sequence for the varying grades of fuel to be bunkered.
15. Make provisions for an early trial use of the HFO to be delivered. This is particularly feasible for systems with dual settling and service tanks (3.3.1, 4:2.1).
16. Confirm that bunkering lines are intact. Confirm that all associated valves are fully operational.
17. Check drip pans and trays around storage tank openings and bunker manifold. Install drip pans plugs and position portable drip pans where needed.
18. Confirm that bunker sampling points are usable. Install sample extraction unit if available. Prepare sample containers (2.6.0, 2.7.5).
19. Confirm method and time of fuel delivery. Confirm size of bunker supply hose and install relevant adapting unit.
20. Schedule personnel routine to allow for anticipated duration of bunkering operations versus personnel rotation.
21. Liaise with deck department for mooring and unmooring of water bound bunker delivery transporter.
22. Consult local regulations with respect to bunkering operations and pollution.
23. Plan boarding arrangements or visit to bunker delivery facility to confirm tank gauges and observe blending process when applicable (2.8.0).

CONTINGENCY PLAN

24. Close deck scuppers (drainage) in consultation with deck department.
25. Position fire fighting equipment at bunker manifold.

26. Position oil absorbent materials near manifold.
27. Establish/review contingency procedures with personnel.

BUNKERING PROCESS

28. Secure water bound bunker transporter.
29. Receive and check bunker delivery note for quantity and quality specifications with the data supplied by the purchasing department (2.5.0).
30. Establish manual and remote communications with transporter (audible and visible communications). Confirm in-house communication.
31. Connect bunker hose and confirm electrical conductivity.
32. Align bunker piping system as per loading sequence.
33. Place shipboard fuel transfer system on manual and record quantity of in-house transfer of fuel during bunkering.
34. Reconfirm ship storage tanks capacity, sounding equipment and method.
35. Check bunker delivery transporter/facility tank gauges. Confirm loading sequence with supplier.
36. Commence loading bunkers.
37. Collect bunker (HFO) samples intermittently. Analyze some of the samples on board if HFO test kit exists (2.7.5).
38. Routinely monitor storage tanks levels. Isolate them as necessary.
39. Close off bunker system upon completion. Take storage tanks measurements and confirm the quantity received. Sign delivery receipt accordingly. Issue protest note to supplier if bunker quantity is less than the allowable tolerance. Return in-house fuel transfer system to normal operating conditions.

40. Disconnect bunker hose and release transporter. Blank off bunker manifold and return all portable equipment to storage location.

41. Dispatch bunker samples as collected to independent laboratory for analysis, preferably to VFQTP or FOBAS. (2.6.0).

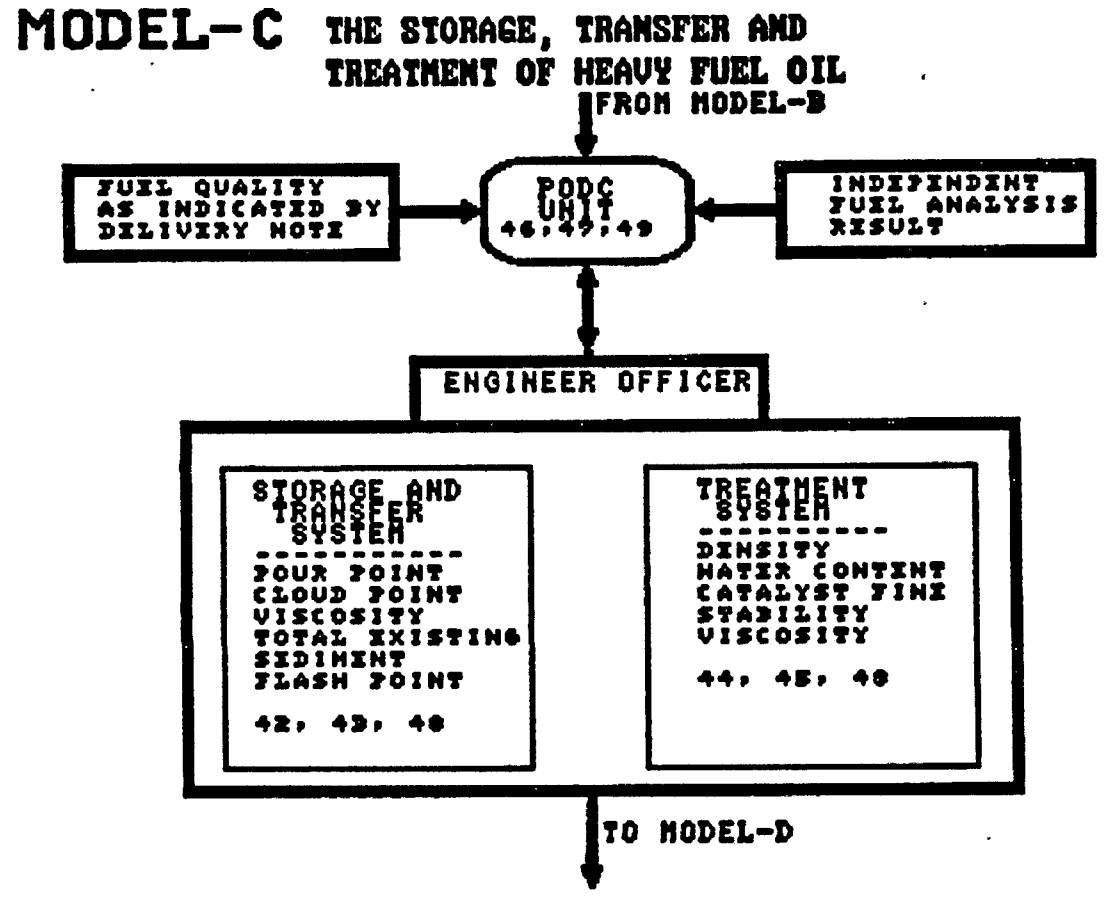
7.6.0 PODC MODEL FOR THE STORAGE, TRANSFER AND TREATMENT OF HFO

Once the HFO has been accepted and stored, the PODC unit has to consider the conditions for proper storage, transfer and treatment of the HFO. The fuel qualities as indicated in the bunker delivery note should be immediately discussed and the applicable parameters and operational conditions should be established as suggested by MODEL-C. Subsequent adjustments to these conditions should be made when the independent laboratory analysis of the HFO becomes available.

The execution of the plan should be delegated to the engineer officer who is responsible for the maintenance of the associated systems. This engineer should be allowed to develop detailed specifics for implementing this plan. The PODC unit should review these specifics as the first step of the controlling function. Secondly, the review process should be a discussional approach with the engineer concerned. This would augment his confidence, experience and knowledge as a participant in the HFO-SYS.

These management activities should be exercised irrespective of whether the fuel is for trial use or full time use. Control methods for determining the effectiveness of the treatment system should be in place,

particularly when a fuel test kit is available. The amount of sludge discharged, or for the newer fully automated centrifuges the frequency of sludge discharge will give a good indication of the fuel stability and the removal of suspended contaminants.



STORAGE, TRANSFER AND TREATMENT ACTIVITIES

42. Based on the pour or cloud points establish storage heating requirements (2.6.0, 3.2.0).
43. Determine minimum pumpability viscosity/temperature and maintain the storage tank accordingly when it is in service (3.3.0).

44. Determine required purification temperature and through put as per centrifuge equipment monogram (3.4.0).
45. Determine the correct gravity disc size and centrifuge equipment operational sequence (3.4.0, 3.7.0).
46. Determine when trial use of the bunkered HFO is feasible. Allow for 24 hours settling time from the completion of bunkering to the actual process through the centrifuge equipment (3.3.1).
47. Make ready settling and service tanks as per provisional arrangement of item 15.
48. Clean all filters associated with the HFO transfer and treatment systems.
49. Start fuel transfer and treatment processes based on item 46.

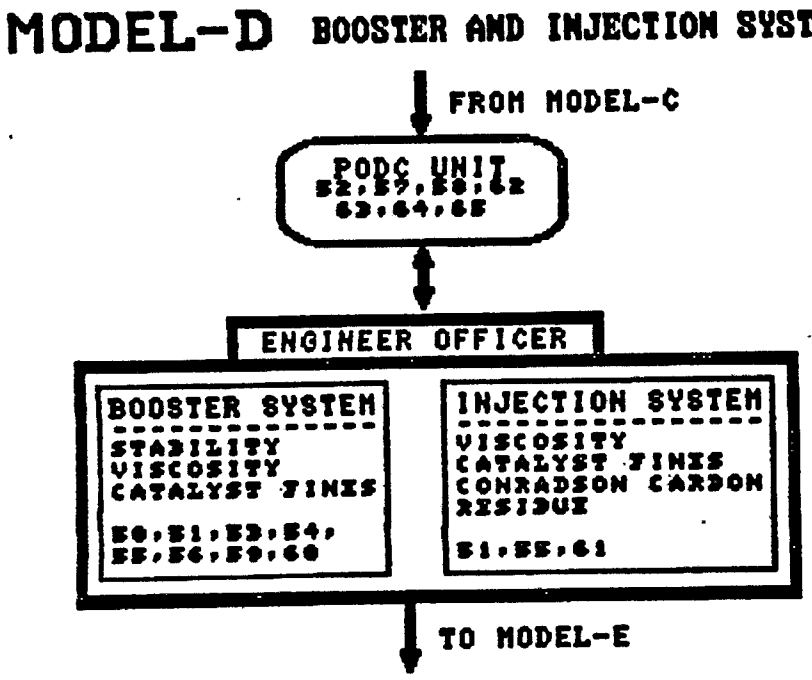
7.7.0 PODC MODEL FOR THE BOOSTER AND INJECTION SYSTEMS

The fuel booster and injection systems are two inseparable systems which the PODC unit should control very closely. The broad plan for these two systems should be developed by the PODC unit. The engineer officer responsible for the maintenance of these systems should be allowed to develop the specifics similar to the considerations in section 7.5.0.

The PODC unit should take particular note of the values of fuel qualities that are likely to create difficulties and include them in the disposition matrix. Based on these findings the maintenance requirement for these systems can be reviewed. It is extremely important that the Chief Engineer creates an effective dialogue with the engineer responsible for maintaining these systems.

The Chief Engineer's experience will provide a substantial support for determining the condition of these systems components. He would be able to identify minute but strategic details which would have otherwise gone un-noticed by the less experienced engineer.

Model-D shows these two systems as a subsystem of the HFO-SYS. The activities which should be planned and implemented are suggested. Equally important for this PODC model is the maintenance of the components of these systems. The condition of these components should be recorded when they are being maintained. Fuel related abnormalities to the physical condition of these components should be noted and the associated fuel quality identified. The cause of all malfunctions in this subsystem should be investigated and documented with reference to the suspected fuel quality.



THE BOOSTER AND INJECTION SYSTEMS ACTIVITIES

50. Clean and ensure proper operation of the PBS de-aeration valve prior to use of new HFO (4.3.0, 4.7.0).
51. Clean all filters associated with the booster and injection systems (3.9.0, 4.2.6, 4.7.0).
52. Determine the required injection viscosity of the HFO (4.2.5).
53. Drain water from the HFO service tank and ensure that the HFO level in the service tank is about the same as the level in the MDO service tank prior to changing over from MDO (4.3.2).
54. Ensure that the pressure setting of the PBS buffer tank is commensurate with the injection temperature, but not exceeding the manufacturers recommended value (4.3.0).
55. To switch from MDO to HFO, gradually heat circulating fuel in the booster system to 85°C or as recommended by the engine manufacturer. Confirm that the fuel injection pumps are uniformly heated prior to switching over. Switch to HFO and gradually heat fuel to obtain required viscosity while maintaining moderate engine loads (4.2.2, 4.2.4).
56. Record fuel flowmeter reading for accountability. Placed viscosimeter in automatic mode when the corresponding injection viscosity has been reached. Bring the engine to normal load conditions (4.2.6, 4.2.5).
57. Maintain the trace heating steam between the booster and injection systems to maintain the fuel viscosity/ temperature as was regulated.
58. Monitor cylinders exhaust gas temperatures for uniformity and the operational condition of injectors and injection pumps (4.5.0, 4.6.0).

59. Observe viscosimeter output signal or viscosity indicator for stability. Monitor the booster pump gland for leakages (4.2.2, 4.2.3).
60. Check overflow piping from mixing or buffer tanks (4.2.2, 4.3.0).
61. Observe fuel injection pump for leakages and abnormalities. Maintain the injector coolant temperature as recommended (4.5.0, 4.6.0).
62. Examine safety filters within the first 48 hours for contaminants irrespective of the indicated condition of these filters (4.2.6).
63. Bring homogeniser on line after the execution of item 62 and not earlier than 24 hours of HFO operation on newly supplied HFO (3.8.1, 3.8.2).
64. Do not adjust VIT based on fuel test results or prior to the execution of Model-E.
65. Based on the evidence from item 62 review centrifuge equipment set-up as per item 45.

7.8.0 PODC MODEL FOR THE COMBUSTION CHAMBER, EXHAUST GAS USERS AND SHUTDOWN PRECAUTIONS

The management of the HFO-SYS culminates in this final model where the effectiveness of the previous models can be measured. Notwithstanding, the activities associated with this model have the greatest effect on the success of this dynamic process.

To achieve unquestionable success this model must be managed by the most senior engineer officer in consultation with the PODC unit. This model will provide substantial feedback which must be used to adjust activities in the preceding models.

The PODC unit must realize that once the fuel enters the combustion chamber several irreversible processes occur. These processes include the energy conversion process, the effects of contaminants on the subsystem components as well as the formation of destructive complexes and pollutants. Although these processes are irreversible, they can be managed.

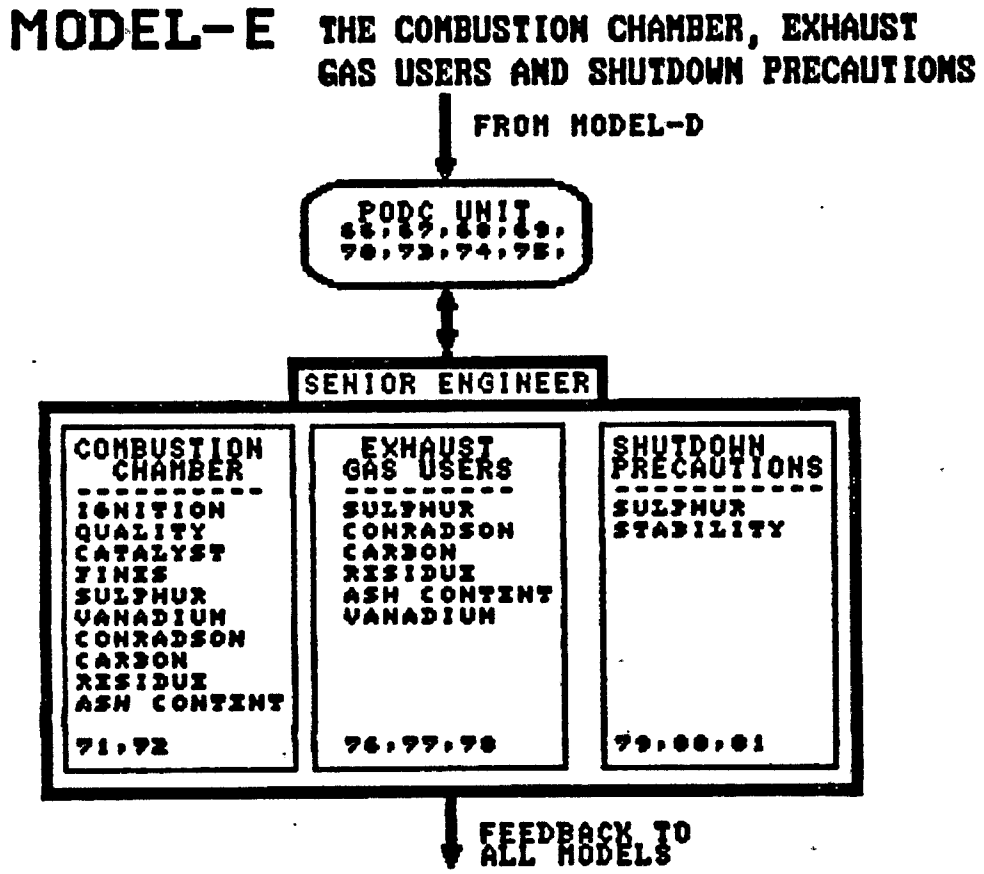
To manage them the PODC unit must have the knowledge and experience of these processes, they must know the equipment associated with these processes, they must have the skills to use the available diagnostic equipment as well as be able to interpret and correlate the findings to the various plans.

The PODC unit is directly responsible for the maintenance of the engine and equipment associated with the HFO-SYS. It is essential that when components are opened up for maintenance that they should be inspected closely for fuel related wear, corrosion, erosion and deposits. Those fuel qualities that are associated with these abnormalities must be identified and the actions taken within the HFO-SYS to deal with these fuel qualities must be reviewed and modified as necessary.

Model-E is a simple diagram which shows that the full discussion of the activities associated with this model should be done by the PODC unit. The senior engineer officer next to the Chief Engineer should be responsible for implementing the plan. The Chief Engineer should limit his participation in the execution of the plans. This will place him in a better position to observe and recognize some of the least apparent difficulties.

Most of the condition and performance monitoring equipment are centered around the components of this model. Therefore the feedback to the other models are illustrated to emphasize the continuity of the management process.

This model also considers the plans for the temporary shutdown of the diesel engine plant. Often engineers neglect the importance of these simple procedures which are designed to ensure that the engine components are protected from corrosion.



THE COMBUSTION CHAMBER AND EXHAUST GAS USERS ACTIVITIES

66. Based on fuel sulphur and vanadium contents establish a compromised coolant temperature versus engine load (5.2.2, 5.2.3, 6.3.1).
67. Consider the type of cylinder lube oil if multiple grades are available (particularly MSE), and the feed rate for manually adjusted lubricators (5.3.1, 5.3.2, 6.4.0).
68. Insure that the turbochargers intake air filters are clean and the charge-air coolers are not dirty (5.7.1).
69. Determine the appropriate charge-air temperature and method of obtaining this temperature (5.7.2).
70. Operate the engine at a designated load for which recent engine internal and external parameter data exist as well as the sea trial and shop trial data.
71. Measure engine internal parameters (6.5.1, 6.5.2).
72. Record engine external parameters. Take particular note of fuel pump index and VIT automatic setting (4.5.0).
73. Compared data from items 71 and 72 with previous records and fuel ignition quality. Adjust manual VIT setting and item 69 (2.6.0, 4.5.0, 4.7.0, 6.5.1, 6.5.2).
74. Remeasure and compare internal parameters as per item 71 and 73 to establish the validity of any adjustments which were made.
75. Monitor MSE crankcase lube oil and apply centrifuge equipment accordingly. Top up system oil to maintain alkalinity (6.4.0).
76. Based on fuel conradson carbon residue content and engine load establish the frequency for cleaning the turbocharger turbine blades (5.7.0).

77. Similarly as for item 74, establish the frequency for soot blowing the waste heat boiler tubes (5.8.0).
78. Ensure that the exhaust gas temperature after the waste heat boiler is above the dew point of sulphuric acid (5.8.0).

PRECAUTIONS AT SHUTDOWN

79. Open turbocharger gas side casing drain valve to prevent the accumulation of weak acids from condensation and the by-products of combustion.
80. Turn engine over periodically as recommended by the manufacturer or at least every 24 hours and apply cylinder lube oil to maintain oil film and the neutralizing feature.
81. Reduce circulating fuel temperature to about 110°C or as recommended to prevent stratification, ageing and gasification in the booster and injection systems.

7.9.0 THE HFO-SYS DISPOSITION MATRIX

The efficient and effective management of a dynamic process does not imply that the process is free from difficulties. Subsequently, good management should review the process and identify possible points of difficulties which can not be controlled by nature of the system limitations and the qualities of the material being processed. These points of difficulties can than be included in a disposition matrix which would represent the flow of the process or the components of the system.

For the HFO-SYS the disposition matrix should be developed to reflect all of the components in the system. The PODC models were plans of operating activities and preventive measures which should be managed. On the contrary, the

development of the disposition matrix should review the operating conditions of and the demands on the components of the system as established by the PODC models relative to the qualities of HFO.

The disposition matrix should highlight anticipated breakdowns, malfunctions and obstructions which would require corrective actions. The anticipated problems should be highlighted relevant to the components concern. The problems should reflect the contributory factors from the qualities of HFO and the operating conditions of the system components.

Examples of what should be included in the disposition matrix are as follows: Fuels with high water content, high carbon residue, high aluminium content and apparent instability will inevitably produce sludge. The use of de-sludging fuel additives do not necessarily eliminate this possibility. Thus, the disposition matrix should highlight that the fuel filters are susceptible to frequent clogging. This anticipated problem reflects the quality of the fuel.

Secondly, the same fuel used in a fully automated modern fuel centrifuge will cause the de-sludging mechanism to operate very frequently. Consequently, the matrix should reveal the possibilities of periodic failure of the centrifuge bowl to close properly or the rupture of the bowl sealing rings. These anticipated problems are due to the frequency of de-sludging which reflects the demand on the component.

The disposition matrix is essential in that it would inform and remind the engineer watch officer. Panic, guesswork and equipment down-time can be reduced substantially. The development of the matrix could be based on reflecting the components as per the individual PODC models or the entire HFO-SYS.

Standard forms can be made which could reflect all possible difficulties. Several copies of the matrix should be made and a copy can be used to highlight anticipated problems each time fresh bunkers are taken. The matrix can also be placed in a computer for easy reference. To assist the PODC unit develop the disposition matrix a machinery failures and causes matrix relative to HFO is attached as annex-F, table VII-1.

ANNEX—F

Table VII-1 Machinery failures and causes matrix relative to the qualities of HFOs

Table VII-1 Machinery Failures and Causes Matrik Relative to The Qualities of HFO

(a) Diesel engines

Item	Failure	F.O. contents and properties considered responsible for causing machinery failure
1. Combustion space, in general	◦ Poor combustion (poor atomization, delayed firing, emission of black smoke, deposit of carbon flower)	• Poor mixing stability • Excessive water content • High viscosity • Vanadium • Sodium • Excessive carbon residue • Excessive asphaltene • Low Cetane index
2. Fuel injection pump	◦ Sticking	• Excessive asphaltene • Excessive insoluble (N-heptane) • Excessive carbon residue • Excessive water content
	◦ Abnormal weardown	• Mixing with catalyst (alumina: silica) • Excessive ash content
	◦ Vapour lock	• High viscosity • Excessive water content • High specific gravity
3. Fuel injection valve	◦ Sticking, weardown & corrosion	• Excessive asphaltene • FCC catalyst • Sulphur content • High specific gravity
4. Cylinder cover (including valves)	◦ Sticking of exhaust valve	• F.O. properties, in general, such as asphaltene responsible for causing poor combustion
	◦ Blow-by of exhaust valve	• Vanadium • Sodium • Excessive carbon residue • Excessive ash content • Excessive water content • Excessive insoluble (N-heptane)
5. Piston & rings	◦ Weardown of ring	• FCC catalyst • Water content (inorganic salts contained in water) • Ash content • Low sulphur (high alkali cyl. oil) • Sulphur content (low temp. corrosion) • Carbon residue • High specific gravity

Table VII-1 cont'd.

Item	Failure	F.O. contents and properties considered responsible for causing machinery failure
5. Piston & rings	• Carbon deposit	• Excessive carbon residue • Excessive asphaltene • Low Cetane index • Poor mixing instability (as a result of poor atomization) • Calcium content
	• Sticking of piston ring	• Carbon residue • Unburnt carbon + excessive cyl. oil supply
	• Abnormal weardown (including corrosion), blow-by, scuffing & crack (induced damages)	• FCC catalyst (alumina·silica) • Increased unburnt carbon due to carbon residue, asphaltene and Cetane index
	• Fouling of scavenging/ exhaust port	• Excessive carbon residue • Sulphur content • Vanadium • High specific gravity
7. Supercharger	• Fouling of turbine (exhaust gas side), surging, corrosion of casing (exhaust gas side)	• Water content • Muddy water content • Unburnt carbon + excessive cyl. oil supply • Sodium composition (formation of ash deposit by combustion) • High viscosity • Sulphur content
8. Piston rod stuffing box	• Weardown of oil scraper ring	• FCC catalyst • Combustion residue • Unburnt carbon + excessive cyl. oil supply
9. System oil	• Fouling and deterioration	• Carbon residue • Asphaltene • Sulphur content • Water content • Viscosity • Increased insolubles (N-heptane)
10. Cylinder oil	• Poor compatibility	• Unsuitable feeding rate of oil or TBN

Table VII-1 cont'd.

(b) Peripheral items of equipments

Item	Failure	F.O. contents and properties considered responsible for causing machinery failure
1. F.O. tank	• Abnormal deposit of sludge	• Poor mixing stability • Poor thermal stability • Excessive water content • Excessive muddy water content
2. F.O. transfer system	• Difficulties in F.O. transferring (clogging in piping)	• Pour point • Viscosity
3. Purifier	• Abnormal deposit of sludge, incapability of purification or poor purification results	• Excessive water content (emulsification phenomenon) • Poor mixing stability • Poor thermal stability • High viscosity • Excessive carbon residue • Excessive asphaltene • High viscosity • Excessive muddy water
4. F.O./D.O. blender	• Clogging of blender unit (deposit of sludge)	• Excessive carbon residue • Poor mixing stability • Mixing of FCC catalyst • Excessive asphaltene content • High viscosity
5. F.O. Heater	• Foulding and clogging	• Poor thermal stability (carbonization and peeling off) • Sulphur content (effects of cupric sulphate)
	• Corrosion of copper elements	• Sulphur content
6. F.O. strainer	• Clogging	• Mixing of FCC catalyst • Poor thermal stability • Excessive carbon residue • Excessive insolubles (N-heptane) • Excessive asphaltene • Excessive muddy water content • Excessive ash content

Source: Japanese Shipowners' Association

CHAPTER VIII

CONCLUSION

The quality of HFO will continue to decrease. The improvements in refining methods which lead to the extraction of more lighter components from crude oil and the introduction of catalyst fines in residual fuels will soon be used extensively around the world. This trend will undoubtedly increase the demand for the ship operator to be well educated as to the implications of the use of HFO.

There are still cases of fuel specification disputes between operators and suppliers of HFOs. The operators of diesel engine plants should adopt the ISO marine fuel specifications for use in their bids to tenders for the purchase of bunkers. Considerations should be given to MODEL-A: 'The Specification of HFO' in order to establish the acceptable fuel quality parameters for comparison to the established ISO grades of fuels. The purchase order to tenders should include limitations on the fuel qualities as determined from MODEL-A.

Once the fuel has been accepted and bunkered, it is than the responsibility of the operator to ensure that the fuel is used efficiently with minimum detrimental effects. The operator should use the available onboard fuel test facilities and independent laboratory (VFQTP or FOBAS) analysis of the fuel is highly recommended.

The storage, transfer and treatment of HFO should be managed as suggested by MODEL-C. New constructions should include multiple tanks design and centrifuges with maximum capacities which are at least three times the maximum fuel consumption of the plant. Fuel stored in dormant fuel tanks should not be allowed to reach their cloud point. The newer generation of centrifuges do not imply that the treatment of HFO is automatically optimum. The treated fuel should be analyzed and fuel safety filters should be checked to validate the effectiveness of the process.

The use of fuel additives is a symptomatic and a remedial approach to the conditioning of HFO. Most of the difficulties encountered from the use of HFO can be avoided by the systematic management of the plant adjustable parameters. The use of additives can only be justified from the development of the HFO-SYS Disposition Matrix. This would indicate where additives could serve as a secondary improvement beyond the limitations of the HFO-SYS components.

The use of homogenisers for the conditioning of fuel is certainly a welcome development. However the location of the homogeniser should always be in the fuel loop to the injection system and never before the centrifuges. The positive aspect by which agglomorates of asphaltenes are reduced will go a long way in alleviating combustion problems associated with instability and incompatibility. To emphasize the importance of this equipment the operator should realize that although the initial stability of the fuel may be good, there is no guarantee that this quality will withstand the high injection temperature. If the homogeniser is employed to produce emulsified fuel as the

first step in the reduction of NO_x than the former situation will be accomplished as well.

The booster and injection systems are without doubt the heart of the HFO-SYS. The activities associated with MODEL-D are all equally important in preparing the fuel for the combustion chamber. Adequate supervision and control of the activities and components associated with this model must be exercised.

The VIT mechanism should be carefully controlled and maintained. The connecting linkages should be checked regularly. This fuel quality adjustment system should be operated strictly by the engine manufacturer recommendations. In no case should the adjustment of the manual fuel quality setting precede the execution of MODEL-E.

The elder generation of slow speed two stroke diesel engines were not designed for the efficient combustion of poor quality fuels above 380 cSt. Their combustion chamber components were not designed to withstand the detrimental effects of extremely poor quality fuels. The system and method of cooling these components are also inadequate for this purpose. The turbochargers are less efficient than the newer ones and for loop scavenge engines the possibility of increased port fouling is extensive.

The installation of the newer generation fuel treatment plant and larger heaters coupled with the use of high quality exhaust valves in these elder generation engines do not necessarily improve the plants capability to burn

very poor quality fuels. The better quality exhaust valves without the bore-cooled valve seat will serve no purpose. It is important that owners of elder generation engines desist from using extremely poor quality fuels at the expense of the safety of the crew and vessel.

For the newer generation engines, the inherent design and operational aspects of the combustion chamber are adequate for the use of the commercially available poorest quality fuel. The extent of their abilities to burn poor quality fuels will not be exceeded within the foreseeable future. The role of the operator in maintaining these abilities is the only limiting criterion relative to the available grades of fuels.

The exhaust gas user equipment are susceptible to fouling from the qualities of HFO and the combustion process itself. Their contributions to the efficient combustion of HFO and the overall thermal efficiency of the plant can be drastically reduced in a short period of time. It is important that the operators establish an adequate program for cleaning these equipment relative to the engine load and fuel qualities.

For the unifuel ship, the medium speed engine is the sensitive element with respect to fuel qualities. Extreme care should be exercised in the treatment and conditioning of the fuel. Monitoring the various engine internal and external parameters should be done relentlessly. The early detection of microseizures could prevent catastrophic damage to the engine.

When diesel engines are stopped the engine components are susceptible to sulphuric acid attack. The lower temperature of the combustion chamber components should be counteracted by maintaining high coolant temperatures. The engine should be rotated periodically and cylinder liner lubricating oil should be supplied to maintain the protective coating and the neutralizing agent on the combustion chamber components.

The engineering staff should keep adequate records of all maintenance activities carried out on the HFO-SYS. When components are opened up they should be inspected carefully and all abnormalities recorded accurately. This record will provide the staff with an excellent assessment of the effectiveness of the fuel management program. Defects in the program can be identified as may be evident from the nature and extent of the recorded fuel related abnormalities.

The engineering staff should develop the HFO-SYS Disposition Matrix to reflect the plant's components and the possible difficulties that could be encountered as a result of fuel qualities and the associated demand of the components. The process of developing this matrix will guarantee that the staff are knowledgeable of the significance and consequences of HFO qualities relative to the plant.

The owners of diesel engine plants should encourage the foregoing activity. They should provide the ship staff with adequate literature on the qualities of HFO and their effects of the diesel engine plant. Owners should involve their vessels in fuel analysis programs. For

marine power plants the shore staff should assist in the interpretation of the fuel quality test results as a supporting function in developing the knowledge of the ship staff.

It is also pertinent that the owners of diesel engine plants should ensure that the types of materials used for the combustion chamber components are known to the ship staff. The type of exhaust valve, cylinder liner, piston and piston rings as well as the method of surface treatment of these components should be known. This would assist them in anticipating the effects of fuel qualities and to observe specific operational parameters as well as maintenance precautions.

The foregoing five paragraphs underscored the need for the training of inservice operators. The shore based staff has a major role in promoting this acquisition of knowledge. Owners should not relent in involving their engineers in training courses and seminars on this subject when these programs are available.

Maritime institutions should dedicate some of their resources to the development of appropriate courses relative to marine fuels for their curriculum. Short term courses for inservice personnel should also be considered. The format of this dissertation should hopefully provide a basis for these courses.

Fuel qualities will not remain as they are. An operator who is educated to systematically manage HFO systems would be a valuable asset in guaranteeing the much needed return on the high investment in the diesel engine plant.

SELECTED BIBLIOGRAPHY

1. Armstrong, Michael. A Handbook of Management Techniques. London: Kogan Page Limited, 1986.

2. Breyer, H. "ISO-Marine Fuels International Standards Development - Status - Introduction and Implications Upon the Quality of Future Marine Fuels." Paper. Castrol Marine, October 1989.

3. Clark, George H. Industrial and Marine Fuels Reference Book. London: Butterworth and Co. Ltd., 1988.

4. CIMAC. "Recommendations Concerning the Design of Heavy Fuel Treatment Plants for Diesel Engines." Paper. December 7th 1987.

5. Det Norske Veritas. Fuel Oil Quality and Fuel Oil Systems. Vol. No. 86-V001. September 1989.

6. Donnelly, James H., Jr., et all. Fundamentals of Management. 6th ed. Plano, Texas: Business Publications, Inc., 1987.

7. Ewart, W.D. Bunkers a Guide for the ship operator. London: Fairplay Publications Ltd., 1982.

8. Institute of Marine Engineers (IME). Conference on Combustion of Fuels in Ships 1979-1985. London: Marine Management (Holdings) Ltd., 1980.

9. IME. Diesel Engine Combustion Chamber Materials for Heavy Fuel Operation. London: Marine Management (Holdings) Ltd., 1990.

10. Gatmalm, Orjan A. "Diesel Exhaust Control." Paper. Institute of Marine Engineers. London, 1991.

11. General Council of British Shipping. "The Storage and Handling of Marine Fuel Oils on Board Ships." Paper. London, 1983.

12. Katsoulakos, P.S. and Thompson, R.V. The Application of Emulsified Fuels in Diesel Engine Designs: Experimental Results and Theoretical Prediction. (Trans.) IME, Vol. 97, Paper 10 (1985).

13. Lilly, L.C.R. Diesel Engine Reference Book. London: Butterworth and Co. (Publisher) Ltd., 1984.

14. Poprawa, Kurt. New Process Designs and Experiences in the Field of the New Generation of HFO Centrifuges and Plants. The Motor Ship Eleventh International Marine Propulsion Conference and Exhibition, March 1989.

15. Shell International Petroleum Company Limited. The Petroleum Handbook. Netherlands: Elsevier, Science Publishers B.V., 1983.

16. Shell International Trading Company (Shell Marine). Lubricants and Fuels in Ships. London: Chorley & Pickersgill Ltd., 1989.

17. Taylor, D.A. Introduction to Marine Engineering. 2nd ed. London: Butterworth & Co. Ltd., 1990.

18. Westfalia. Treatment Systems for Heavy Fuel Oils. Westfalia Separator AG., 1984.

19. Wilbur, C.T. and Wight, D.A. Pounders Marine Diesel Engines. 6th ed. London: Butterworths & Co. Ltd., 1984.

20. Woodyard, D.F. Marine Propulsion and Future Fuels. London: IPC Industrial Press Ltd., 1979.